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RESEARCH ON THE GEOMAGNETIC FIELD

Soviet scientists and scientists from a number of other countries marked the second decade in space with intensive experimental and theoretical research on the solar wind, the structure of the "calm" geomagnetosphere, the space-time structure of the development of substorms, and the extent of magnetism among the planets of the solar system.

The results achieved in this period include proof of the solar origin of interplanetary fields and determination of the relationship of the sign and magnitude of interplanetary fields to the sign and magnitude of the total magnetic field of the visible face of the sun.

Another important result was the proof of the role of a mechanism of reconnection of the force lines of interplanetary and geomagnetic fields in the formation of the characteristic shape of the geomagnetosphere and its basic features: asymmetry in the day-night direction, the formation of "funnels" on the day side at high latitudes (polar cusps), and the formation of a magnetic loop on the night side.

Reservoirs of solar wind plasma energy such as polar cusps, the plasmosphere, the plasma layer in the loop, radiation belts, and the vast reservoir of magnetic energy known as the geomagnetic loop formed by these processes play an enormous role in the development of a number of geophysical processes and geosolar couplings. Although the radiation energy of the solar wind is 100 times greater than the energy contained in interplanetary magnetic fields, it is the instability of the latter that determines the mechanism by which energy stored in the atmosphere and arriving upon a change in solar activity is realized in the form of the interrelated and simultaneously occurring phenomena known as magnetic, ionospheric, auroral, and radiation storms.

Processes of interaction in the boundary region of the magnetosphere and the solar wind, processes on the boundaries between the closed force lines which take part in the rotation of the earth and the open lines controlled by the solar wind, and processes of the annihilation of oppositely directed force lines in the loop of the magnetosphere lead to the formation of global electrical fields in different parts of the magnetosphere. These electrical fields directly determine the nature of plasma convection and magnetic force lines and the nature and topology of the current systems flowing in the earth's magnetosphere and ionosphere during periods of "calm" and disturbances.

Direct measurements of electrical fields and the discovery of currents along the force lines, which H. Birkeland discussed as early as 1896, constituted the experimental basis for global models of current systems called on to explain electromagnetic storm mechanisms.

A detailed survey was made of a region of the magnetosphere at distances of 3 to 7 R3, where in 1964 the satellites Elektron-2 and Elektron-3 were the first to detect the magnetic field of a quiescent current ring and where the current system responsible for the main phase of a magnetic storm (the D_{st} variation) develops during storms.

Significant advances have also been made in the use of space- and ground-based equipment to study low frequency electromagnetic field fluctuations and the interaction of fields and particles.

Researchers began to successfully employ artificial injection of plasma into the atmosphere in order to study details of magnetospheric processes. Although the scales of these model experiments were small by comparison with natural observations, they may be carried out under controlled initial conditions and their importance is hard to overestimate. Such experiments have been successfully conducted in the Soviet Union.

One of the most important advances of the second decade in space was the establishment of a cause-and-effect relationship between the signs and magnitude of individual components of the interplanetary magnetic field and the level of disturbances on the earth and the nature of variations of the magnetic field in near-polar regions on the surface of the earth. This led to the development of an effective and practically important method of determining the sign of the interplanetary magnetic field on the basis of data from magnetic observatories located in the vicinity of the geomagnetic poles.

Also of practical importance are possible relationships between solar activity and meteorological processes due to the effect of interplanetary fields and the geomagnetic field. It is possible that the study of such effects will lead to a better understanding of the complex processes which determine weather genesis factors.

The second decade in space was also marked by a detailed study of the geomagnetic field's structure determined by the distribution of internal sources. It is sufficient to remind the reader that prior to direct satellite measurements of the geomagnetic field, experiment data had made it possible to determine six harmonics ($n = m = 6$), that is, 48 coefficients of a Gaussian series which analytically represents the geomagnetic field. Now 13 and more harmonics (more than 195 coefficients) have been determined.

Research conducted by Soviet and American scientists revealed that geomagnetic field anomalies reflecting the structure and tectonics of the earth's crust extend to the altitudes at which satellites orbit. This has provided new opportunities for studying the crust, problems of global geology, and the natural resources of the earth by means of satellites.

Major advances have been made in studying an ancient problem of natural science, namely the problem of the origin of the geomagnetic field. It is in this light that we should first examine the discovery of a magnetic field on the planet of Mars (the Mars-2, Mars-3, and Mars-5 automatic Martian stations), the discovery of a magnetic field on Mercury (the Mariner-10), the direct study of Jupiter's magnetic field (Pioneer-10, Pioneer-11), a detailed study of the paleomagnetic fields of the Moon (Apollo, Lunokhod-2), the discovery of the Venutian magnetosphere, and the study of the upper limit of its magnetic moment (Venera-9 and Venera-10).

These studies led to the determination of topological characteristics of planetary magnetic fields which have left no doubt that planetary magnetic fields are due to the same mechanism, namely dynamic processes in highly conductive molten cores.

A very important result of experimental studies of planetary magnetism was the fact that it first became possible to test the reliability of different models of geomagnetism within the framework of comparative planetology.

The beginning of the second decade in space coincided with the last years of one of the first postwar international geophysical projects, namely the "World Magnetic Survey of 1957-69."

The well-known geophysicist C. Chapman, in recounting the history of this major scientific undertaking [1], places its origin in 1950, when, in the Soviet Union, on the basis of a proposal made by the Director of the Institute of Geomagnetism of the Weather Service of the USSR, N. V. Pushkov, construction of the nonmagnetic schooner, the *Zarya*, began. Built in Finland and equipped with Soviet-made equipment, this schooner began taking measurements of the magnetic field in the World Ocean in 1956, where no measurements had been taken since 1929 after the wreck of the American schooner, the *Carnegie*. 41 countries took part in the World Magnetic Survey, which involved land, sea, air, and space measurements. The emblem of this project consisted of the most advanced magnetic survey vehicles of the time: the *Zarya* schooner, the *Magnet* airplane, and a satellite, with a globe in the background (Figure 1).

Figure 1. The emblem of the "World Magnetic Survey" project.

The Danish geophysicist V. Larsen was appointed chairman of the World Magnetic Survey Committee of the International Association of Geomagnetism and Aeronomy and served from 1963 to 1969, while the Soviet geophysicists N. V. Pushkov (1963-67) and Yu. D. Kalinin (1967-69) were appointed vice-chairmen, and the American geophysicists E. Westin and A. Zmuda were appointed general secretaries.

The measurements provided data on the components of the magnetic field and magnetic declination and inclination in many regions of the globe. The *Zarya* took measurements on routes with a total length of approximately 500,000 kilometers, while Canadian and American *Magnet* planes took measurements on routes totalling 3,800,000 kilometers. These surves of the magnitude and direction of the magnetic field in the vicinity of the Earth's surface constituted an important part of even more informative surveys conducted by means of the

Kosmos-49 (1964), OGO-2 (1965), and OGO-4 satellites. During these surveys the satellites measured the field scalar using absolute proton and quantum magnetometers.

From 1968 to 1970 the Soviet Union and United States conducted secondary global surveys using low flying satellites in order to continue their studies of the spatial structure of the geomagnetic field and its secular variations and external ionospheric magnetic field sources. These studies made it possible to obtain regular and extensive data on the scalar of the magnetic field needed to construct more refined analytical models of the geomagnetic field and study its secular variations.

Satellites were deployed in high apogee orbits in order to make a detailed study of constant external magnetic field sources located in the outer magnetosphere and in the vicinity of its radiation belts. In addition to magnetometric studies, the satellites were used to make extensive studies of plasma in the geomagnetosphere. The combination of magnetic and plasma data made it possible to draw a complete picture of the earth's magnetosphere on a calm day.

In combination with extensive studies on the earth's surface in the polar regions, experiments for studying electrical fields, and the aforementioned studies of interplanetary fields, these studies made it possible to shed light on many aspects of the mechanisms of magnetic disturbances and magnetic substorms in all their geophysical manifestations.

STUDYING THE GEOMAGNETIC FIELDS OF INTERNAL SOURCES

The Kosmos-321 satellite, equipped with a magnetometer for measuring the magnetic field scalar, was deployed on a near polar orbit on January 20, 1970. The satellite stayed in operation for more than two months.

The initial orbital altitude was 280 kilometers at the pericenter and 507 kilometers at the apocenter. With the orbit inclined 71 degrees to the plane of the equator, it shifted longitudinally westward in relation to the Earth at a rate of -2.62 degrees per day, while its pericenter shifted toward the equator at a rate of 1.92 degrees per day. The orbit and its evolution engendered favorable conditions for measurements on 94% of the surface of the globe and for studying phenomena in polar auroral ovals. The agreement of the readings of a KTsM-1 cesium quantum magnetometer with absolute values in the range of measurable fields was checked by means of comparing them with the readings of a proton magnetometer. The agreement was within 2 gammas. A special thermostatic system enabled normal functioning of the spectral lamp and absorption chambers outside the thermal container of the satellite. The magnetometer's sensors were located in a container separated from the body of the satellite by means of a 3.6 meter long rod. Nevertheless the experiment was affected by deviation caused primarily by thermal currents in the fasteners of the rod and the container. The rotation of the satellite made it possible to detect the effect of deviation in the form of modulation with the period of rotation of the satellite. These effects were filtered out in data processing. Data was recorded on a memory on 4 to 5 orbits per day.

The primary experiment data processing program made it possible to convert measured quantities into magnetic field units, determine the coordinates of the satellite at the time of

measurement, determine the theoretical field at measurement points, and determine the difference between measured and computed field values. The algorithms for the primary data processing program were developed by workers at the Institute of Geomagnetism, the Ionosphere, and Radio Wave Propagation (IGIRWP) and the IKI. This information constituted the initial information for putting together a "Catalogue of Measured and Computed Values of the Geomagnetic Field Strength Modulus Along the Orbits of the Kosmos-321 Satellite" (1976) [3]. In 1967 a "Catalogue of Measured and Computed Values of the Geomagnetic Field Strength Modulus Along the Orbits of the Kosmos-49 Satellite" [4] had been put together and disseminated.

The results of the world magnetic survey were sent to international data centers in Moscow, Maryland, Sjarlaton Lund (Denmark), and Kyoto, Japan and served as the basis for a number of analytical models of the geomagnetic field and for studying secular variations and the structure of geomagnetic field sources.

THE INTERNANATIONAL MODEL OF THE GEOMAGNETIC FIELD FOR THE 1965 ERA

The study of the wide variety of new geophysical phenomena detected by space and ground surveys required a single analytical model of the geomagnetic field which would adequately represent the aggregate of new experiment data. For example, this model could be used as a reference for detecting the anomalous fields of internal sources and the fields of external current systems, for determining the topology of the force lines which control the motion of charged particles captured by the geomagnetic field, and for determining points on the earth's surface which connect one and the same magnetic field force lines (conjugate points), where many phenomena occur synchronously and identically in both hemispheres of the planet.

The subject of an international geomagnetic field model was first discussed at the 12th General Assembly of the International Geophysical and Geodesic Union in Helsinki (1960). Further discussions of this topic led to agreement on a number of initial requirements which the model would have to satisfy. Tests of a number of models which had been constructed in a number of countries were undertaken. Criteria for the adequacy of one model or another included the accuracy of representation of data from the Kosmos-49 and OGO-2 satellites and the accuracy of representation of magnetic field components on the earth's surface. N. P. Benkova, Sh. Sh. Dolginov, L. O. Tyurmina, and T. N. Cherevko delivered the Soviet report on this topic. Histograms of differences ΔT between different models selected for the international model and measurements taken by the Kosmos-49 are given in Figure 2.

After quite lengthy discussions, a synthesized field model which took into account models developed on the basis of satellite data and components of the field on the earth's surface was chosen. It is represented by a Gaussian series from internal sources with a number of spherical harmonics $n = m = 8$ in terms of components in geocentric coordinates for a spherical Earth with a radius of 6371.2 kilometers. The users of the model were advised to take into account the ellipticism of an earth with an equatorial radius of $A = 6378.16$ kilometers and an oblateness $f = 0.0033529$.

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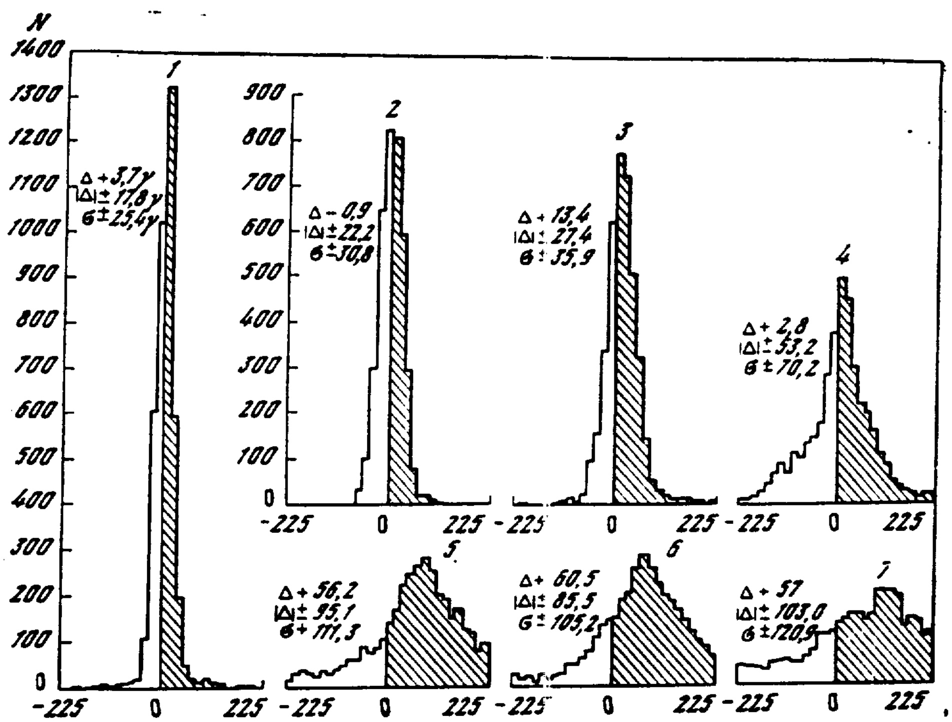

Figure 2. A comparison of different analytical models of the geomagnetic field with experiment data from the Kosmos-49 satellite
Histograms of the most frequently encountered differences Δ T between measured field values: 1. data from the IGIRWP 2. POGO 3. GSFC 4. Fougere 1 5. Gurvich et al. 6. Leaton et al. 7. averaged model

The model was developed for the 1965.0 era. When this model is used for the 1955.0-1972.0 period one must introduce corrections for harmonic coefficients:

$$C_n^m(t) = C_n^m(t_0) + \dot{C}_n^m(t - t_0),$$

where C_n^m is equivalent to the secular variation of the factors in gammas per year.

The model was approved by a working group on October 24, 1968 in Washington, then approved by a special committee of the International Association of Geomagnetism and Aeronomy in February, 1969, and was officially adopted in Moscow at the 15th Assembly of the International Geophysical and Geodesic Union in 1971.

Thus, instead of the previously used model consisting of 48 coefficients (n = m = 6) the Union recommended the use of a model containing 80 coefficients and their first time

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derivatives $\dot{g}_n^m$ and $\dot{h}_n^m$ which give a better representation of the main geomagnetic field whose sources are located in the molten conductive core of the earth. For the 1965.0 era the central inclined dipole of the international model had a magnetic moment of 8.01 times 10 gauss per cubic centimeter. It intersected the earth at points φ = 78.6 degrees N and λ = 290.2 degrees E and φ = 78.6 degrees S and λ = 110.2 degrees E.

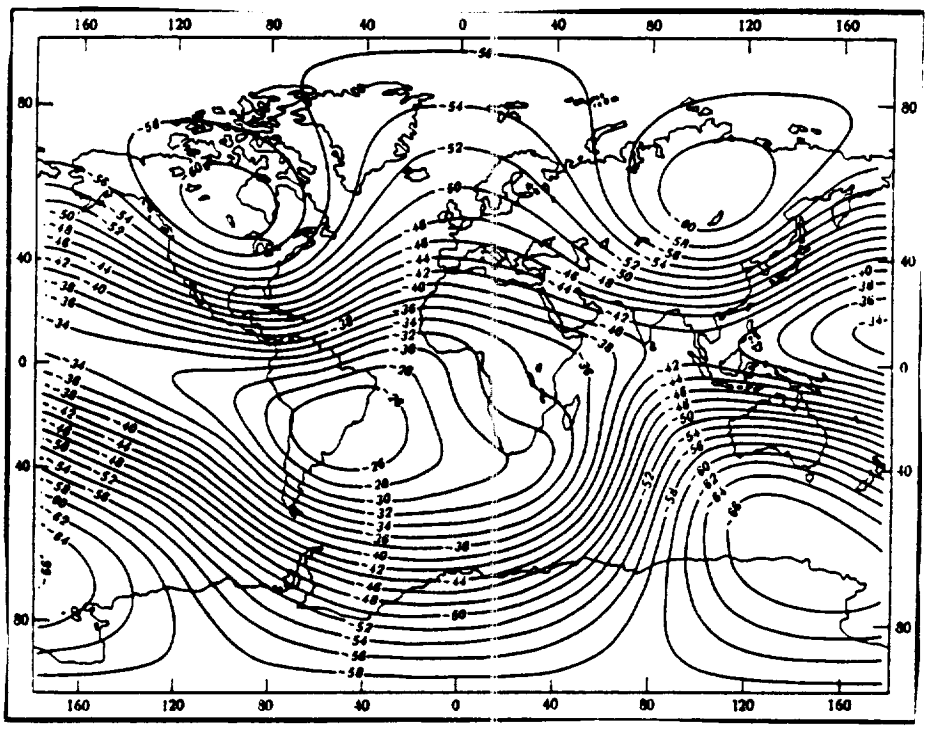

Figure 3. A map of the isolines of the scalar of the complete vector T of the International Analytical Model of the Geomagnetic Field for the 1965 Era (International Analytical Model (IAM))

The international analytical model was used to produce maps for seven magnetic field elements and their secular variations. The T and δ T maps of the international analytical model are given in Figures 3 and 4. The General Assembly of the International Association of Geomagnetism and Aeronomy in Kyoto (Japan, September, 1973) recommended that the

IAM of 1965.0 be retained as a standard until 1975.0. In 1975 the IAGA Assembly in Grenoble adopted an IAM for the 1975 era, which was recommended for use in the period from 1975 to 1980 [8].

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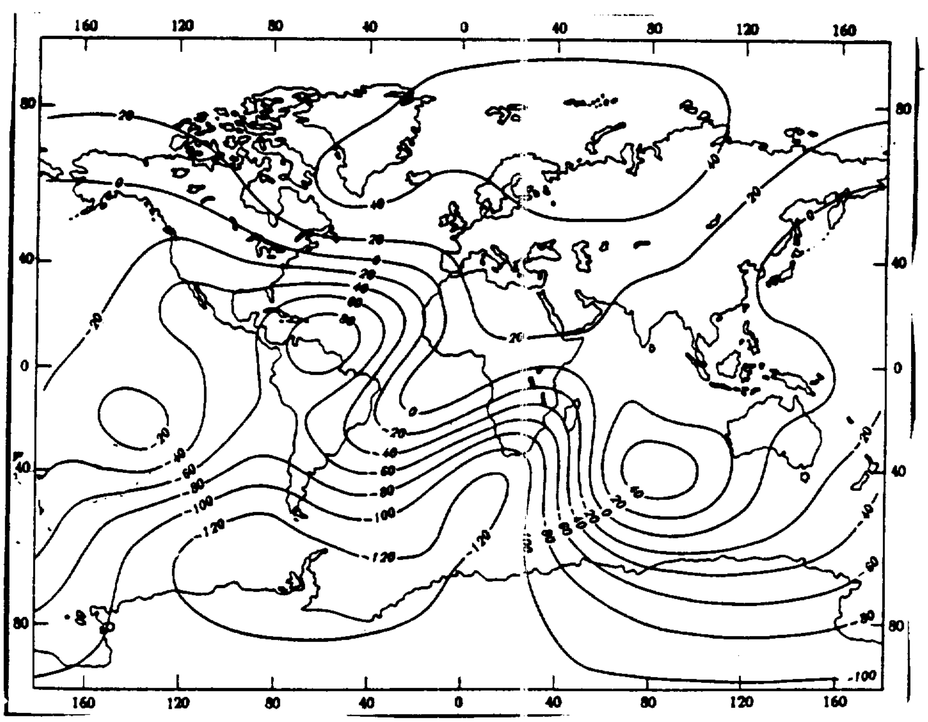

Figure 4. A map of the isolines of identical secular variation of the scalar δT of the IAM

GEOMAGNETIC FIELD MODELS BASED ON DATA FROM THE KOSMOS-321 AND KOSMOS-49 SATELLITES

Magnetic surveys from the Kosmos-321 and OGO-6 satellites made it possible to obtain analytical models for the 1970 era and study the secular variations of the geomagnetic field for the five years after the adoption of the IAM and the Kosmos-49, OGO-2, and OGO-4 experiments.

Measurements taken by the Kosmos-321 at 12,000 points were used to obtain an analytical field model, and spherical harmonic analysis was carried out to n = m = 9, that is, taking into account 99 coefficients of the Gaussian series. The model was published in [7].

Improvements in computer software and hardware made it possible to develop analytical models with longer series than the IAM. The need to make the series longer was dictated by a number of circumstances.

Each harmonic in a spherical series has a wavelength equal to L/n kilometers, where L is the length of the circumference of a terrestrial meridian (approximately 40,000 kilometers). A model with $n = 8$ takes into account the characteristics of a field about 5,000 kilometers long, that is, longer than the dimensions of the earth's molten core. Thus there were grounds to assume that the main field could be best represented by a series much longer than $n = 8$.

The long wave component of the field may be represented by a spherical harmonic series with $n = 25$, corresponding to a wavelength of approximately 1600 kilometers. However anomalies associated with structural characteristics of the crust may have the same wavelength. In any case one can confidently assert that the IAP model does not fully reflect the main geomagnetic field.

The method of utilizing the field scalar in spherical harmonic analysis developed by J. Cain and D. Jensen [9] made it possible to use a stream of experiment data from satellites to determine longer analytical field series. However this was limited by computer capabilities, because an increase in the number of harmonics in a series to n is accompanied by an increase in the number of terms in the series to $(n + 1)^2 - 1$. These limitations were overcome by using state-of-the-art computers and other mathematical techniques. V. I. Kolesova and E. P. Kropachev carried out spherical analysis of the geomagnetic field to $n = 23$ on the basis of ground data [10].

J. Cain computed an analytical model of the geomagnetic field ($n = m = 22$) for the 1970 era. In addition, the model contains secular variation coefficients up to $n = 14$. N. P. Benkova and T. N. Cherevko [12] determined an analytical model of the geomagnetic field to $n = m = 12$ solely on the basis of data from the Kosmos-49 satellite.

The high harmonic coefficients of different models with longer series differ noticeably. Consequently, individually the high harmonic coefficients do not reflect the distribution of anomalies, which, generally speaking, is random. However expanded models which account for high harmonics provide better agreement with satellite-measured magnetic field values than the IAM does. Describing the geomagnetic field with longer spherical series made it possible to proceed to clarification of the geological meaning of the difference T between measured and computed values of geomagnetic field strengths along the orbits of the Kosmos-49 and OGO satellites.

CRUST-GENERATED ANOMALIES AT THE ALTITUDES OF LOW-FLYING SATELLITES

In 1965 the first publication devoted to the Kosmos-49 experiment [13] contained the idea that anomalies associated with the structure of the earth's crust could be detected at the altitudes at which the Kosmos-49 flew.

Anomalies can be detected by analyzing the differences $\Delta T = T_m - T_{an}$. A field should be represented analytically by a sufficiently long series, however the minal wavelenghs of the series should be "longer" than the waves of the anomalies in question.

A magnetometer used to determine the field scalar measures the main field and the projections of anomalies onto the direction of the main field. The intensity of anomalies at satellite flying altitude is on the order of several gammas and may be lower than field variations due to external sources, which are particularly significant at high latitudes. Thus the best conditions for detecting magnetic anomalies occur at low latitudes during very magnetically calm periods and involve the use of minimal-altitude satellites.

In 1970 American scientists [14] published a comparative map of the differences ΔT between measurements taken by the Kosmos-49 and OGO satellites and computed field values with a series length of n = m = 9, which gave evidence of the detection of anomalies associated with the lithosphere. A similar map of ΔT differences in the same latitude range was plotted in the Soviet Union (Figure 5) [15] and revealed that with a series length of n = m = 9 the differences ΔT retain traces of the main magnetic field not associated with the crust. In the same year such "intermediate" anomalies were detected in global maps plotted by American scientists for latitudes of plus or minus 50 degrees on the basis of OGO satellites.

Thus, it has become clear that crust-generated anomalies can be detected more reliably by means of using longer analytical series. In a study published in 1973 N. P. Benkova and T. N. Cherevko [12] revealed that the use of data obtained solely from the Kosmos-49 satellite could be used to extend the series to n = m = 12. Further lengthening of the series is accompanied by an increase in computational errors.

Maps of the differences ΔT between satellite-measured and computed field values with a series length of n = m = 13 were plotted by American scientists using a combination of data from the Kosmos-49 and OGO satellites.

Figure 6 gives a map of the anomalous field of Africa plotted on the basis of Kosmos-49 data [16]. Isolines at 4 gamma intervals were drawn on the basis of average values of ΔT in 5 by 5 degree blocks. According to the results of an aeromagnetic survey, the Bangi Anomaly in Central Africa has an intensity of approximately 700 gammas at an altitude of 3 kilometers from the surface. At an altitude of 350 kilometers its intensity is approximately 20 gammas. The anomaly extends 900 kilometers latitudinally. The assumption that its sources lie in the mantle would have led to impossibly high field intensities in the mantle (100 oersteds). A comparison of magnetic and tectonic maps reveals a certain correlation between them. The Bangi Anomaly coincides with a tectonic uplift zone between the Chad Basin in the North and the Congo Basin in the South. Thus, the ΔT map reflects anomalies associated with the lithosphere. The value of these maps is difficult to overestimate. There is no doubt that special purpose experiments conducted at miminal satellite altitudes could make it possible to obtain the experiment data needed to construct a model of the earth's crust. Its structure could be studied in the quickest and most inexpensive way over the entire earth in remote regions of the World Ocean and continents. Such a comprehensive survey would make it

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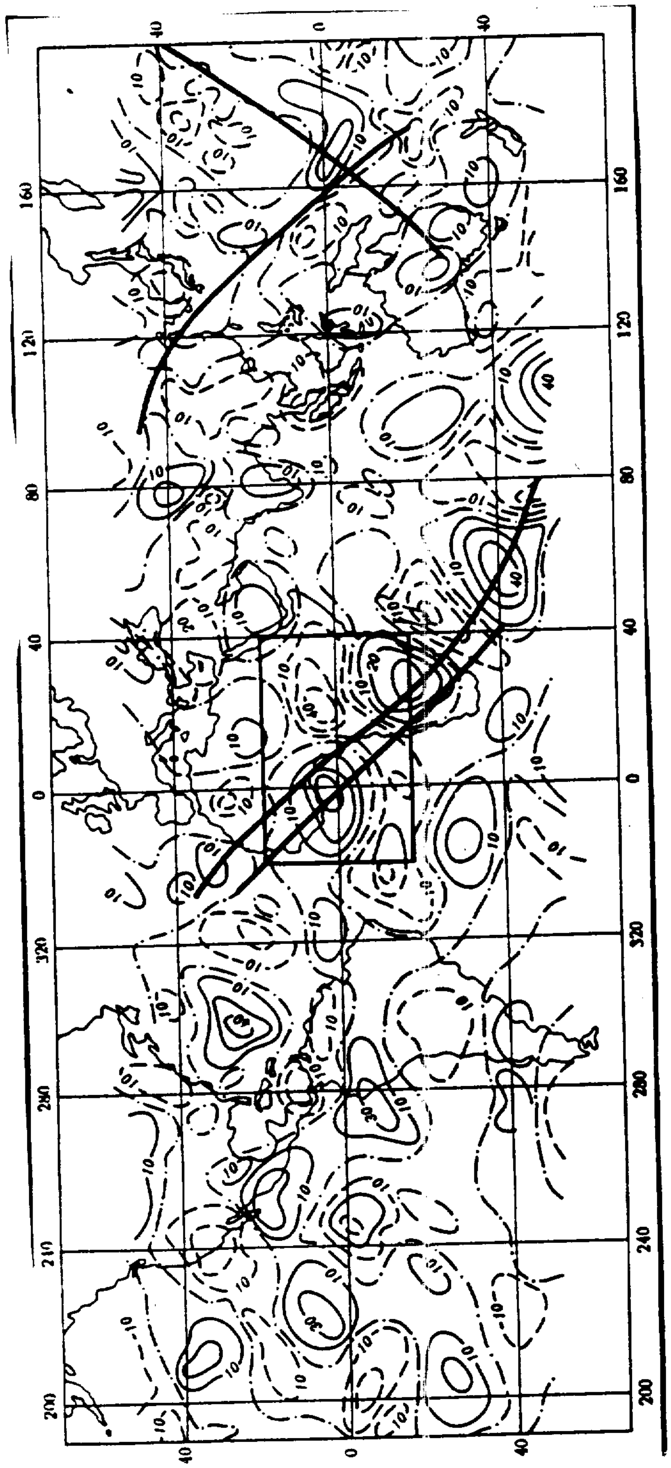

Figure 5. Differences ΔT between measured values of T (Kosmos-19) and the analytical series n = m = 9.

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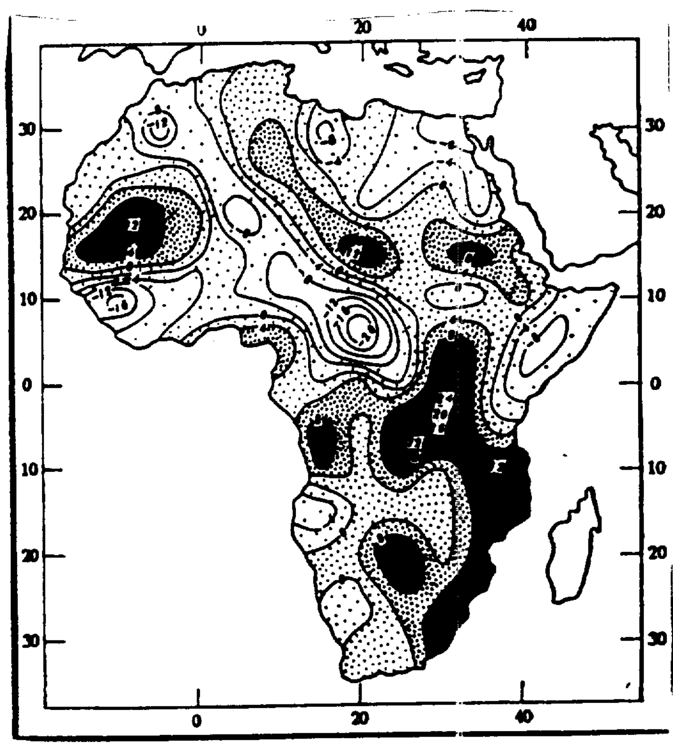

Figure 6. The anomalous field of Africa. The difference between Kosmos-49 data and the analytical series n = m = 13 (according to [16]). The anomalies reflect the structure of the earth's crust. Isolines at 4 gamma intervals.

possible to detect boundaries of contemporary geological features of the crust which have still not been investigated and to clarify the past evolution of the crust.

Existing global maps of ΔT bear certain traces of the irregularity of initial data and the effect of disregarded errors, which are sometimes comparable to the detected anomalies. For example, residual ΔT fields plotted on the basis of OGO data are "distended" along the meridians due to the polar orbits of this satellite, and ΔT differences plotted on the basis of data from the Kosmos-49 are "distended" in the direction of the Kosmos-49's orbits.

Great opportunities for studying both the main and anomalous fields will be provided when it becomes possible to take precise measurements of both the field scalar and the components of the field. In order to measure field components with an accuracy of 5 to 10 gammas at altitudes of 300 kilometers, one needs to know the orientation of the satellite with an accuracy to within 10". Overcoming these difficulties will provide geophysicists with new opportunities.

Satellite measurements of anomalous fields constitute one effective way of studying the fundamental question of modern geophysics: namely, is the crust of the ancient shields and platforms magnetic?

SECULAR MAGNETIC FIELD VARIATIONS

The particular interest of geophysicists in secular geomagnetic field variations is due to two circumstances.

1. The spatial and time pattern of secular variations of the contemporary geomagnetic field must be known in order to correct magnetic maps and analytical geomagnetic field models. This is required by a number of applied problems.

2. Secular geomagnetic field variations constitute a unique source of infroamtion on processes in the earth's molten core to which the geomagnetic field owes its existence.

There have been direct observations of the geomagnetic field for approximately 350 years. Initially only magnetic declination was measured, by seafarers.

A map (Figure 7) of the secular variation of the scalar of the full vector of the geomagnetic field T illustrates the basic characteristics of the secular variation of the modern geomagnetic field. The map was plotted on the basis of global surveys conducted in 1964 by means of the Kosmos-49 and OGO satellites, a second survey conducted in 1970 by means of the Kosmos-321, and on the basis of data from a network of ground magnetic observatories obtained during this five year period [17]. The dashed lines connect points where the field diminished, while the solid lines connect points where it grew stronger. The lines are known as "isopores," namely lines where secular variations are of the same intensity.

First we must focus our attention on the oval regions in which field variations are particularly great ($\delta T \sim 150$ gammas per year). These constitute secular variation "centers."

They arise and disappear at different points on the globe. One such center existed in the 30s in the vicinity of the Caspian Sea, but in the 40s and 50s it shifted and disappeared.

On isopore maps of preceding eras there was a positive focal point northeast of Kergelen Island with field variations of up to 40 to 60 gammas per year, but now in this location field variations amount to only 10 to 20 gammas per year.

On the map we can see a negative focal point of $\delta T \sim$ 30 gammas per year west of Japan. The birth of this center was observed by Japanese observatories in 1955. Now it is recorded by observatories in Irkutsk, Tashkent, and Alma-Ata. The peak has moved west. All this reminds one of a wave process.

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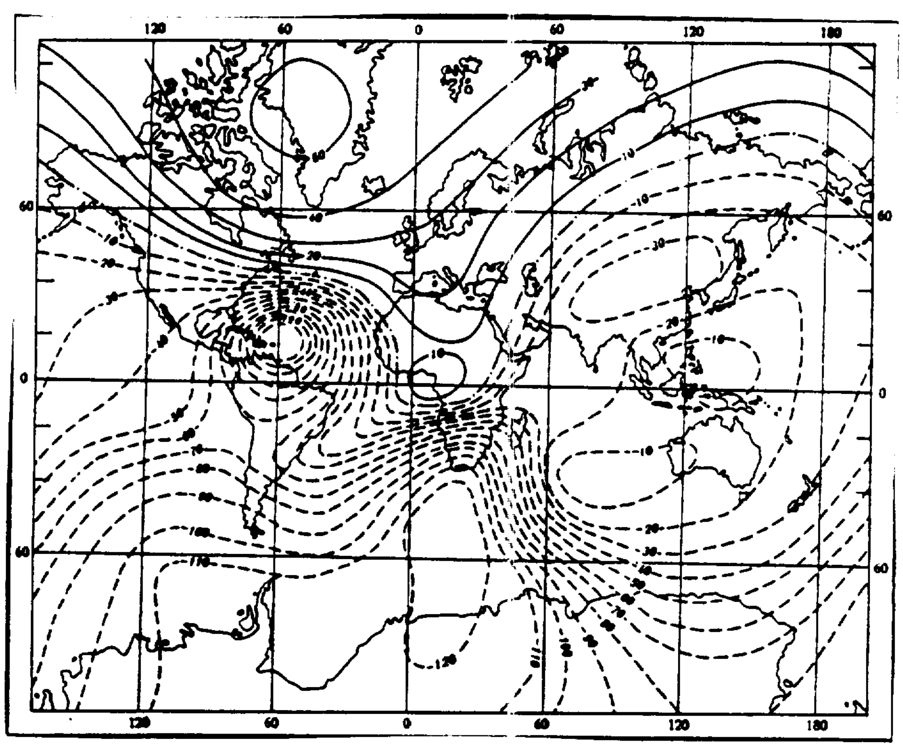

Figure 7. A map of the lines of identical secular variation of the geomagnetic field scalar based on Kosmos-321 data [17]

On the isopore map it is apparent that the regions where the field is diminishing are much more numerous than the regions where it is getting stronger. We can compare the negative and positive variations by means of the sums

$$\sum_i^n \Delta T_i \Delta S_i = \Phi_i,$$

where ΔT_i is the average variation of a field on an area of ΔS_i bounded by adjacent isopores. The index i indicates the variable number of the area ΔS. This product is of the same magnitude as flux and is measured in maxwells.

Positive changes amount to 1.44 times 10^{14} maxwells, negative changes 19.43 times 10 maxwells, while the change $\Delta\Phi$ = -17.99 times 10^{14} maxwells, that is, on the whole over the earth field strength has dropped at the same average rate. However the field has not changed in the same way in the northern and southern hemispheres. In the southern hemisphere the field has only gotten less intense ($\Delta\Phi$ = -13.43 times 10^{14} maxwells), while in the northern hemisphere at latitudes of approximately 60° it has gotten more intense, but the overall field of the northern hemisphere has gotten less intense ($\Delta\Phi$ =-4.6 times 10^{14} maxwells).

The asymmetry of the change in the field relative to the geographical equator indicates that some of the geomagnetic field has somehow drifted north. A comparison of this map with secular variation maps of the preceding decade (described in the collection *Uspekhi SSSR v issledovanii kosmicheskogo prostranstva. Pervoye kosmicheskoye desiatiletiie 1957-67* (Soviet Advances in Space Exploration. The First Decade in Space (1957-67), Moscow, Nauka, 1968.) revealed that the zero (or neutral) isopore is moving quite rapidly to the north. The following quantity is used as a measure of field asymmetry

$$(\Delta\Phi^S - \Delta\Phi^N)/\Delta\Phi.$$

A similar pattern had been observed previously, on the basis of data from observations made over the last 150 years [18, 19].

So what was so important about satellite measurements? They made it possible to determine quickly and globally the main features of secular variations and demonstrated the possibility of not only determining secular variations, but also their rate of change, that is, not only the first but also the second derivative of the process. This has given us confidence that the use of satellites for purposes of permanent secular variation research will enable a comparatively quick resolution of the main problems which arise in the comparison of secular variations on the basis of contemporary archeomagnetic and paleomagnetic data.

In particular, periodic satellite-aided high precision global surveys of the strength and direction of the modern geomagnetic field constitute the most effective way to solve the following problems of geomagnetism and the planetary mechanism:

1. What sort of spectrum do secular geomagnetic variations have and what is their role in the field generation mechanism [20, 22]?

2. Is the diminution of the energy of the modern dipole field due to dissipative processes in the core or to the self sustained oscillatory nature of the geomagnetic field. Wouldn't the energy of the dipole field be transferred to higher harmonics whose energy should increase in this case [23, 24]?

3. What are the cause and the effect in the observed correlation between changes in the rates of secular variation and changes in the rotation speed of the Earth [27-31]?

4. How do the earth's magnetic and gravity fields vary in relation to one another [25, 26]?

Another promising direction is investigating the general properties of secular variations as one manifestation of a dynamic process within the framework of comparative planetology. The most promising planet is Jupiter.

STUDYING EXTERNAL SOURCES OF THE GEOMAGNETIC FIELD

Geomagnetic studies conducted on the earth's surface as early as the 19th Century indicated the possibility of the existence of external geomagnetic field sources. These hypotheses were formulated in a very general form in 1898 by A. Schmidt, who, 60 years after Gauss, represented the field on the surface of the earth as a sum of potentials from internal V_i and external V_e sources $V = V_i + V_e$, by generalizing the formula for a Gaussian series.

Studies of the distribution of charged particles and magnetic and electrical fields conducted in the first two decades in space by all countries have made it possible to establish the reality of the existence of a number of current systems, determine their location in space, and clarify at least the main features of the mechanisms responsible for their occurrence.

The Earth's magnetosphere, which is determined by the operation of the main dipole field and external sources in the form of equivalent current systems, is depicted in Figure 8. The identification of individual current systems and the clarification of the physical mechanisms for their occurrence is quite justifiably associated with the solution of a number of problems of magnetospheric physics which define the overall mechanism of complex geosolar couplings.

Let us examine the contribution of Soviet scientists to the current portrait of the geomagnetosphere.

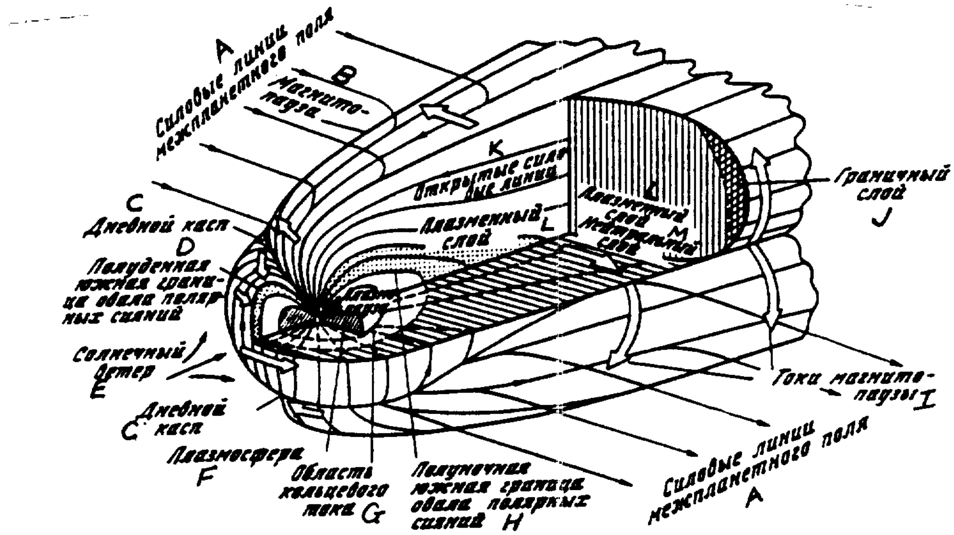

Figure 8. A model of the geomagnetosphere [45]

Key: A. interplanetary field force lines B. magnetopause C. day cusp D. noon southern boundary of the polar auroral oval E. solar wind F. plasmosphere G. ring current region H. midnight southern boundary of the polar auroral oval I. magnetopause currents J. boundary layer K. open force lines L. plasma layer M. neutral layer

THE FIELD OF HIGH LATITUDE SURFACE CURRENTS

Although the microstructure of the boundary of the magnetosphere is considered a topic of debate, it is generally believed that the boundary of the magnetosphere is a layer along which current flows, generating pondermotor forces which enable the existence of a magnetic squeezing effect.

In 1959 the Soviet physicists V. N. Zhigulev and Ye. A. Romishevskiy [32] predicted the main characteristics of the topology of the geomagnetic field when a flux of solar plasma is flowing over it: the formation of a shock front, the formation of critical points with “zero” field strength, where plasma may flow inside, and the drift of force lines to the night side.

In 1960 the British physicist J. W. Dungey indicated [103] that the reconnection of interplanetary magnetic field and geomagnetic field force lines was the mechanism by which force lines drifted from the day side to the night side, forming a region of reduced magnetic field strength at hight latitudes on the day side and a magnetic loop on the night side.

This is not the only possible mechanism, although its effectiveness in controlling magnetic activity has been proven. S. I. Syrovatskiy [35] ascribes an important role to Kelvin-Helmholz instability effects in the formation of the loop. The boundary of the magnetosphere is not ideal, and a portion of magnetic flux diffuses into the plasma and vice versa. This deviation from the ideal is responsible for the existence of a very weak magnetic field component normal to the surface of the magnetosphere, which is indispensible for further stages of force line drift and the formation of a loop on the night side.

The Explorer 12 satellite was used for the first very detailed studies in the boundary region of the magnetosphere. These studies stimulated theoretical calculations of the shape of the magnetospheric boundary, or magnetopause. Meade's [38] and Meade and Williams' [38] models were the best known at that time. American spacecraft (Explorers 10, 12, 14, 18, 26) surveyed the magnetosphere at low latitudes. A comparison of experiment data on low latitudes and Mead and Williams' model found them to be in satisfactory agreement.

The Elektron 2 and Elektron 4 satellites were the first spacecraft to survey the magnetosphere at higher latitudes, and the Elektron 4 surveyed the higher latitude magnetosphere on the day side.

The first experiment data revealed that in contrast to low latitudes the magnetic field on the day side at high latitudes is attenuated even in magnetically quiet times. An increase in the disturbance of the field weakens it even more, at least in the initial period of the disturbance. This characteristic of the high latitude magnetosphere was described in general terms by theoretical models [36, 37], although a later more detailed analysis revealed noticeable deviations. A. Ye. Antonova and V. P. Shabanskiy [39] developed modified models of the magnetosphere which provided a better description of the topology of the high latitude magnetosphere. Figure 9 presents the results of a comparison of measured values of with model calculations at different latitudes at a distance of 9 R3 [40]. The discrepancies between measurement results and the models are most significant at high latitudes. This is manifest to an even greater extent when one compares the models with experiment results near the noonday hours (LT 0.9 to 13 hours).

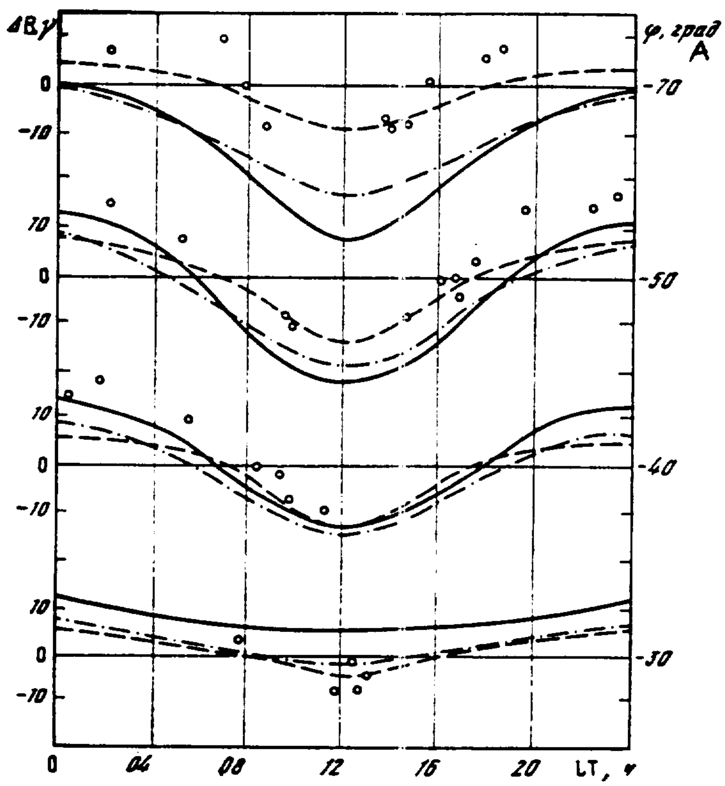

Figure 9. A comparison of measured differences ΔT (points) with theoretical values for different models of solar wind flow over the geomagnetic field (according to [40]).

Key: A. degrees

High latitude magnetic field variations revealed the existence of a near noon minimum which is described only in general terms by the modified model [39]. This indicates that a special local current system exists in this region.

The location of the magnetopause at high latitudes according to data from the Elektron 4 is illustrated in Figure 10. As we can see, at a latitude of 74 degrees there is a minimum distance to the magnetopause of 8.9 R3. The orbit of the Elektron 4 did not make it possible

to survey higher latitudes. This distance, as Ye. G. Yeroshenko and A. Ye. Antonova observed [40], differs very little from a theoretical estimate of the minimum distance from the tip of the "funnel" in the area of the neutral point indicated in [36].

The attenuation of the field at high latitudes during disturbances observed by the Elektron 4 was 30 to 50 gammas. A definite correlation was found between it and the sign of the interplanetary field and indices of activity, and the seasonal variations of the position of the magnetopause were determined in relation to the incline of the axis of the dipole.

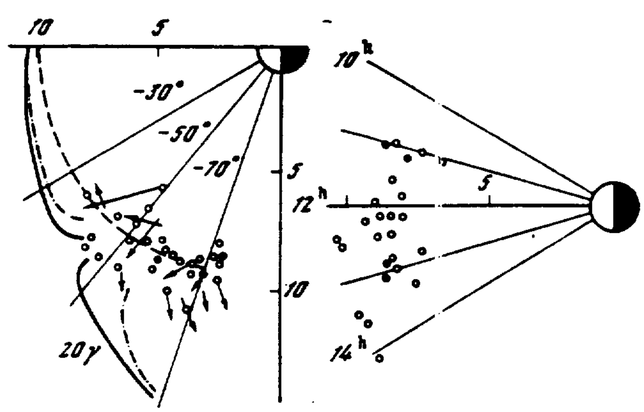

Figure 10. The position of the magnetopause on the basis of data from the Elektron 4 satellite in a region bordering the "funnel" or cusp.

The "funnel" drifts somewhat from lower geomagnetic latitudes in local winter to higher latitudes during the equinox. As we have already mentioned, the orbits of the Elektron 4 did not make it possible to study the "funnel" completely, but the main features of this region were discovered.

In 1965 V. D. Pletnev, G. A. Skuridin, V. P. Shalimov, and I. N. Shvachunov [41] made a more detailed examination of a model of the current system in the vicinity of neutral points. A diagram of the current system (Figure 11) depicts the topology of the "funnel" and the signs of the arrows of the current conception of the high latitude day magnetosphere. We should note that the authors of [41] provided the most specific statement of the problem of the role of neutral points in the mechanism of particle injection into the magnetosphere. At that time this topic was a matter of heated debate.

The IMP-5 was the first American satellite to take measurements of the magnetic field on the day side up to latitudes of 75 degrees. In 1972 Fairfield and Ness reported [42] that at distances of more than 6 R3 there is a permanent wide region centered around the polar cusp (the cusp is another word for "funnel" used in [40]). Field strength at 7 R3 on force

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lines closed on the day side is 50 to 70% of that of an undisturbed dipole field. The disturbance of this region and the lack of a clearly defined magnetospheric boundary agree with data from the Elektron 4 and the studies cited above. Fairfield and Ness were the first to report that field perturbations, which got as high as 45 gammas in the vicinity of the polar cusp, ran approximately perpendicular to the average position of the field, which indicated the existence of currents along the force lines.

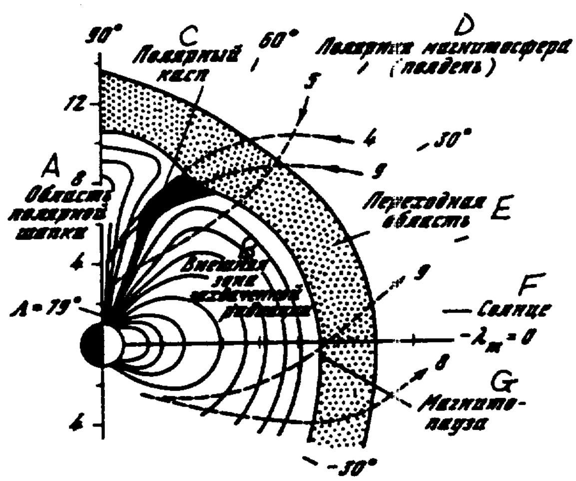

Figure 11. A model of the magnetosphere in the vicinity of the polar cusp. Dashed curves indicate the trajectories of the IMP-5 satellite.

Key: A. polar cap region B. outside zone of captured radiation C. polar cusp D. polar magnetosphere (noon) E. transitional region F. sun G. magnetopause

Solar wind plasma, or more precisely plasma of solar origin, enters the magnetosphere from the transitional zone between the shock front and the boundary of the magnetosphere through the polar "funnels." Plasma from the "polar funnels" affected by electrical and variable magnetic fields winds up in the plasma layer of the loop and in a ring current of captured radiation. L. Frank [43] obtained proof of direct penetration of protons and electrons from the transitional zone through the polar "funnels" of the day side. One can find an overview of experiment data and a discussion of injection mechanisms in the reports of Frank [44] and Heikkila at the COSPAR Symposium in Madrid in 1972 and in Frank's overview [46].

EXTRAIONOSPHERIC QUIET DAY RING CURRENT

The characteristic weakening of the horizontal component of the field of low latitude observatories during magnetic storms has long been ascribed to the effects of a ring current encircling the earth. A simplified model of this current system in the form of linear current made it possible to estimate [47, 48] that the current is located at distances of 3.5 R3. Subsequently this was confirmed by direct experiments.

However the hypothesis that extraionospheric ring current also exists during magnetically quiet periods at distances of 3 to 4 R3 was first stated on the basis of measurements taken in 1959 by the second Soviet space rocket Luna-2 flying over these distances [49]. In analyzing these data primary importance was ascribed to the fact that measurement results were less than calculation results. The difference diminished as one moved from three to six earth radii, where the difference was close to zero. This effect may be ascribed to the effects of protons, which at that time had still not been detected in the outside radiation zone. The authors of [49] assumed the existence of protons at distances of 3 R3 in order to explain a field defect by their diamagnetism in a dipole field.

In 1962 Davis published data on the detection of a proton belt by the Explorer 12 satellite. S. Akasofu, J. Cain, and S. Chapman [51] calculated the magnetic effect of the quiet protonosphere. A year later Heppner published the results [52] of measurements taken by the American Explorer 10 with a quantum magnetometer on board. The measurements were taken only once on an ascending orbit and also detected negative ΔT at distances of 4 R3 and positive ΔT at greater distances. This effect was explained either by the effect of a current ring located at a distance of 3 R3 or the effect of surface currents of the boundary region of the magnetosphere. As a rule, the data from the Explorer 12 and Explorer 14 applied to distances greater than 5 R3 and the question of the existence of the current ring was still unresolved.

In 1964 the Elektron 2 and Elektron 4 satellites began taking measurements [53, 54]. Differences ΔT on all orbits had the following characteristics: at distances of 3 to 6 R3 they had negative signs. Average differences ΔT at distances of 3.5 R3 amounted to approximately 65 gammas, at 4.0 R3 45 gammas, at 5 R3 15 gammas, and 6 R3 0 to 5 gammas. A certain asymmetry in the differences ΔT was observed on forward and return orbits: on the return (high latitude and prenoon) sections of the trajectories the ΔT curves were more gently sloping in nature.

As one gets farther away from the earth differences ΔT get smaller, and as one gets even further away, the differences change sign in certain regions. An analysis of $\Delta T = 0$ regions revealed their relationship to magnetic activity: with a decrease in magnetic activity $\Delta T = 0$ regions are found at higher geocentric latitudes and greater distances. In addition, $\Delta T = 0$ had very pronounced seasonal variations: radial distances of $\Delta T = 0$ shifted from 7.5 R3 at the end of January 1964 to 5 R3 at the end of April. In the process latitude shifted from $\varphi = 59$ degrees to $\varphi = 52$ degrees. All this left no doubt that negative ΔT reflect the effect of a source located at these distances and the dynamics of the magnetosphere inside the geomagnetic envelope under the action of more remote sources.

Negative ΔT regions (from maximumΔT to $\Delta T = 0$) on forward and return orbits are 160 degrees apart longitudinally and encompass the evening-night-morning hour sector. It is in this sector that one can interpret the results in terms of "ring current." The values of ΔT at different distances given above apply to the average values of all days which differ with respect to magnetic activity. These differences are the same in terms of the sign of the effect and are close in magnitude to theoretical estimates of the effects of a captured proton field of the model proposed in [51] and are approximately 2 times greater than the magnetic effect of a model of the quiet protonosphere developed by Hoffman and Bracken [55]. However observations did not reveal any reduction in ΔT at distances close to 3 R3, which was predicted by theoretical models of magnetic effects.

The differences ΔT at distances of 4 to 10 R3 published by Cahill and Bailey in 1967 (on the basis of Explorer 10 satellite data) changed sign in exactly the same way as differences T detected by the Elektron satellites. Heppner, who in 1967 [57] compared the Elektron data with Explorer 10 data at distances of 3 R3, pointed out that they agreed and differed from the theoretical curve in the vicinity of 3 R3. This article summarized the results of experimental and theoretical research of "ring current" conducted to 1964 inclusively.

In 1971 Sigiura, Ledley, Skillman, and Heppner [58] published the results of detailed surveys made by the OGO-3 and OGO-5 satellites by means of scalar rubidium and component ferrosonde magnetometers (OGO-5) at distances of 2 to 22 R3. This was the most detailed global survey of the magnetosphere and lasted almost two years, covering space from the equator to the poles. The survey was conducted for the purpose of studying external magnetic field sources in the geomagnetosphere, checking the results of previous studies, and determining the location and energy spectrum of the protons responsible for external magnetic fields during magnetically quiet and magnetically disturbed periods. The abundance of experiment data made it possible to determine characteristic differences ΔT on particularly calm days ($K_\rho = 0$ to 1) and slightly disturbed days ($K_\rho = 2.3$).

Figure 12 gives the average values of ΔT in the vicinity of the geomagnetic equator and at high latitudes (Elektron-2, Elektron-4) at the noon and midnight meridians as a function of distances from the earth. The dashed curve represents the distribution ΔT of "ring current" from the calm protonosphere in Hoffman and Bracken's model. In general, experimental ΔT curves agree with Elektron data and earlier studies.

In a report delivered at the 15th Plenary Session of COSPAR [59] (Madrid, May 10-24 1972), M. Sigiura, remarking on the differences in absolute values of ΔT determined on the basis of Elektron data at a distance of 3 R3 and OGO-3 and OGO-5 data wrote that, "their observations agree to a great extent qualitatively with the results given here, both with respect to -ΔT and +ΔT. It is interesting that Yeroshenko et al. (1966) and Dolginov et al. (1965) observed an increase in $\pm\Delta T$ on magnetically disturbed days and took them into account in similar conceptions of the topology described here."

The magnetic effect of captured radiation is integral in nature. Hence it is less suprising that all space experiments detected the main features of the distribution of ΔT, despite the differences in the orbits and durations of the experiments.

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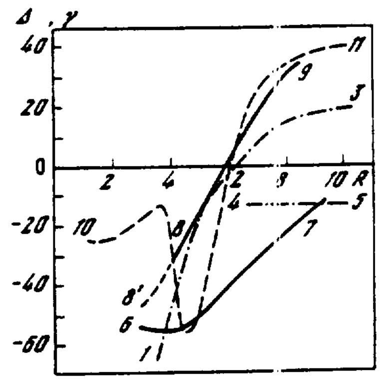

Figure 12. Differences ΔT at distances of 3 to 10 R3 at low and high latitudes on the day and evening sides according to Elektron-2, Elektron-4 (1964), and OGO-3 and OGO-5 (1971) data. Curves 1-2-3 and 4-5: Elektron; + Δ T on the evening side at high latitudes; - Δ T (1-2 and 4-5) the same on the day side Curve 6-7: midnight, equator, OGO; 8'-8-9: noon, equator, OGO; 10-11: Hoffman-Bracken model

The situation is different with the detection of protons responsible for the observed magnetic effects. In this case differences in orbits and the spectral characteristics of the instruments used had a greater effect. As we have already mentioned, Davis and Williamson, using Explorer-12 satellite data, were the first to indicate that protons in an energy band of 0.1 to 4.5 megaelectronvolts with a peak intensity at R3 had been detected [50]. These data were confirmed by experiments conducted with the Explorer-14 and Explorer-15 satellites. Frank, using data from the OGO-3 [46], reported the existence of a belt of protons with energies of 0.2 to 50 kiloelectronvolts with a peak intensity at a distance of 6.5 R3 during magnetically calm periods.

Apparently, the protons of this energy band do not determine the field depression at a distance of 3 R3. During a magnetically calm period the Explorer-45 detected a peak proton energy density of 2 times 10^{-7} per cm^3 on a force line intersecting the equator at a distance of 3.5 R3 in an energy band of 5 to 872 kiloelectronvolts. It is natural that the geomagnetic field acts like a spectrograph and in fact we have a proton belt in a rather wide continuous spectrum. The boundary of this spectrum is determined by the strength of the field capable of confining charged particles. Appropriate estimates of the relationship between radiative energy density and magnetic energy in the dipole field have been made by Dessler and Parker [60] and Skopke [61]: $\Delta T/T_0 = -2\ E/3\ E_M$, where ΔT is the magnetic field of ring current on the surface, T_0 is geomagnetic field strength at the equator, E is the total energy of the proton band, and E_M is the external magnetic energy of the geomagnetic field. According to Davis' estimates [50], the total energy of protons with energies greater than 97 kiloelectronvolts is 1.5 times 10^{22} ergs. According to Frank's estimates [44], the total energy of protons with energies between 0.2 to 50 kiloelectronvolts is 4.8 times 10^{21} ergs. The field of the ring on the earth's surface $\Delta T = 38$ gammas.

Nevertheless there are several reasons for considering the existence of two current systems: an inner system with a peak at a distance of 3 R3 and an outer system with a peak at a distance of 6.5 R3, as Frank [44] and Sigiura [58] have suggested.

As we have already mentioned, during quiet periods the peak is located at a distance of 6.5 R3, where $\Delta T = 0$. Movement of the proton peak towards the Earth during disturbances is in accord with the movement of the $\Delta T = 0$ region revealed by Elektron data. The authors of [62] pointed this out.

Cahill and Bailey were the first to make a detailed study of the magnetic effect of disturbed ring current during a magnetic storm, using the Explorer-26 satellite during the storm of April 17-18, 1965. However as early as 1964, the Elektron-2 satellite detected major field depressions during a magnetic disturbance in

the night sector [53]. In the process it was observed that significant local depressions were observed several hours after the sudden onset of the disturbance but long before the main phase developed, at the same time as a polar disturbance began to develop. But the effect was not a ring effect in nature. This agrees with current notions that the main phase of a storm is a continuous sequence of magnetic substorms.

Thus, the reality of the permanent existence of an extraionospheric current ring, which was most convincingly demonstrated in 1964 on the basis of the results of magnetic measurements taken from the Elektron-2 and Elektron-4 satellites, was proven for once and for all by a number of later experiments carried out by means of magnetometers and plasma sensors. At these distances, an asymmetric current ring of magnetic substorms develops during magnetic disturbances.

The fact of the constant existence of an external magnetic field source was taken into account by adding the harmonic g_1^{0e} to the spherical harmonic series [63].

EXTRAIONOSPHERIC AND IONOSPHERIC POLAR CURRENT SYSTEMS OF A MAGNETIC STORM

In early March, 1970, the Kosmos-321 satellite, whose orbit was inclined at a 71 degree angle to the plane of the equator, crossed the polar ovals in the northern and southern hemispheres at altitudes of 260 to 300 kilometers and crossed the region of the equator at altitudes of 240 to 335 kilometers in the day and night hours close to magnetically-active layers of the ionosphere.

On March 4, measurements were taken during an isolated substorm when the axisymmetric portion of the field of the storm (DR) was still small. From March 8 through 10, 1970, the most intensive storm of those observed during the 1970 solar activity cycle developed. The American satellite

OGO-6, which was also equipped with a quantum magnetometer, took high-altitude measurements at the same time as the Kosmos-321.

The experiment data obtained were used to analyze several problems of the morphology of a disturbance field:

1) the degree of correspondence between the spatial pattern of a storm as determined by "instantaneous" satellite measurements and the spatial pattern as determined by ground stations; the positions of the ovals;

2) the distributions of negative and positive ΔT or the correlations between the eastern (evening hours) and western (morning and night) electrojets;

3) The correlations between ΔT at high latitudes and the ring current field DR.

These topics were examined in publications [64, 65]. Examples of magnetograms T (that measured minus the field of internal sources) along the orbits of the Kosmos-321) during the main phase of the storm and when the storm was dying down are given in Figure 13. The dashed curves represent the fields of the axisymmetric portion of the field DR on the basis of ground data allowing for the asymmetry of the effect and under the assumption that the portion of the field induced in the earth is the same on the surface and at satellite flight altitudes. In addition, the figure also includes $\delta T = \Delta T$ - DR curves. Comparative data from the Kosmos-321 and OGO-6 at the magnetic equator (J = 0) are given in Tables 1 and 2. According to these data:

a) most of the field depression during a storm has one and the same sign on both satellites and on the surface of the earth, which indicates the extraionospheric origin of the source;

b) during the active phase of a storm measured values of T exceed DR by 25 to 50 gammas ($\delta T = \Delta T$ - DR>0) in the morning, while in the evening sector DR is greater than ΔT ($\delta T<0$). This effect was manifest in the readings of both satellites. The author of [64] hypothesized that in the morning hours this effect may be due to the action of the electrojet, while in the evening it may be due to the possible effect of western current in the ionosphere. At the final stage of the storm recovery phase the identical values of ΔT and DR in the morning hours according to the data of both satellites indicate the attenuation of ionospheric current systems at low latitudes.

The effects of a disturbance at high latitudes are illustrated in Figures 14 and 15 in combination with data from ground observatories. They indicate that:

a) during a period of intensive magnetic activity on the earth the satellites reveal regions where spatial field gradients are quite different from the gradients of the main geomagnetic field. In the areas surveyed, these regions coincide quite well with the position of the polar auroral oval determined on the basis of ground data taking into account the activity index Q and the D_{st} variation during the observation period;

b) the most magnetically active regions are those in the vicinity of the near polar boundary of the oval, where the high latitude boundary of the region of unstable radiation is located.

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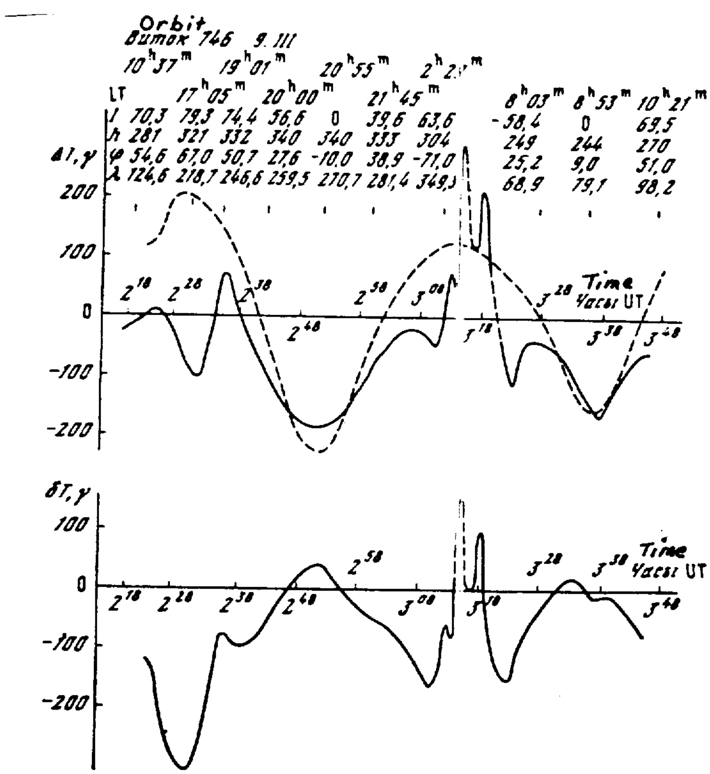

Figure 13. The differences ΔT along the orbit of the Kosmos-321 during the storm of March 8-10.

Dashed curve: calculated field DR according to data from a network of ground equatorial stations at different longitudes

Lower curve: difference $\delta T = \Delta T - DR$

Kosmos-321 magnetograms recorded during the substorm of March 4, 1970 [65] indicate that:

a) there exists a region of positive ΔT with a center at 0400 and a region of negative ΔT with a center at 1600 hours MLT;

b) negative ΔT in the northern hemisphere from 1300 to 1800 hours MLT are due to a weak eastern electrojet. This agrees with data obtained from the OGO-4 and OGO-6 satellites.

The magnetograms in Figures 14 and 15 were discussed on the basis of notions of the existence of an oval which is eccentric relative to the magnetic pole and along which there is the greatest probability of observing polar aurorae, magnetic disturbances, and a number of other geophysical phenomena [67-69].

Table 1

Таблица 1

A Дата и виток	B «Космос-321», h = 242 км			
	Часы LT F	Часы UT G	ΔT, γ	DR, γ
9. III, 744	8 ч 54 мин H	0 ч 36 мин I	—223	—167
9. III, 745	8 54	2 06	—193	—148
9. III, 746	8 54	3 37	—173	—163
10. III, 760	8 54	0 41	—60	—70
10. III, 761	8 54	2 11	—60	—50
	C «ОГО-6», h = 410 км			
	Часы LT	Часы UT	ΔT, γ	DR, γ
	7 ч 40 мин L	0 ч 00 мин M	—220	—190
	7 40	1 42	—150	—140
	7 40	3 24	—150	—165
	7 40	0 54	—60	—55
	7 40	2 30	—42	—65

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Table 2 Таблица 2

Дата и виток A	D «Космос-321», h = 340 Часы LT F	Часы UT G	ΔT, γ	DR, γ
8. III, 744	J 20 ч 50 мин	K 23 ч 51 мин	—220	—288
9. III, 745	20 50	1 23	—185	—234
9. III, 746	20 50	2 52	—190	—239
10. III, 760	20 50	23 56	—50	—64
10. III, 761	20 50	1 27	—62	—64
10. III, 762	20 50	2 56	—62	—62

E «ОГО-6», h=1050 км Часы LT F	Часы UT G	ΔT, γ	DR, γ
N 19 ч 40 мин	O 0 ч 54 мин	—210	—240
19 40	2 36	—210	—245
19 40	0 06	—90	—70
19 40	1 42	—70	—64
19 40	3 24	—75	—64

Tables 1 and 2. Key: A. date and orbit B. Kosmos-321, h = 242 km C. OGO-6, h = 419 km D. Kosmos-321, h = 340 E. OGO-6, h = 1050 km F. LT hours G. UT hours H. 0854 hours I. 0036 hours J. 2050 hours K. 2351 hours L. 0740 hours M. 0000 hours N. 1940 hours O. 0054 hours

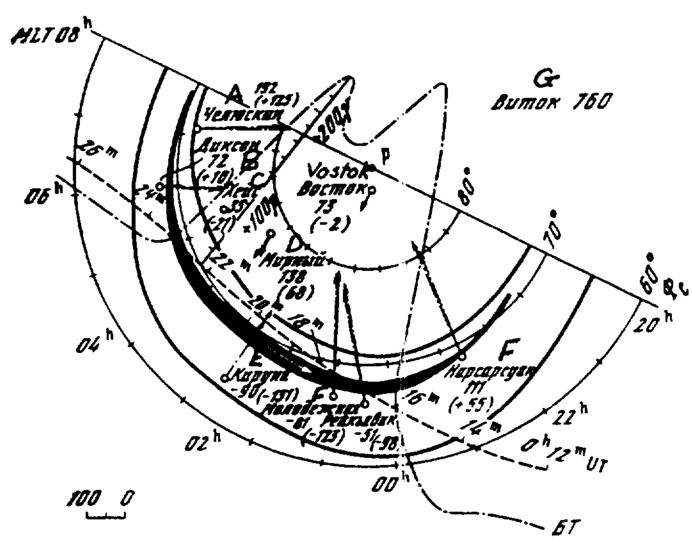

Figure 14. A model of the polar electrojet on the basis of data from the Kosmos-321 and a network of ground stations

The arrows indicate the values of the perturbed vector of the horizontal component H, while the numbers in brackets indicate the values of Z.

Key: A. Chelyuskin B. Dixon C. Haight D. Mirniy E. Kuprina F. illegible G. orbit 760

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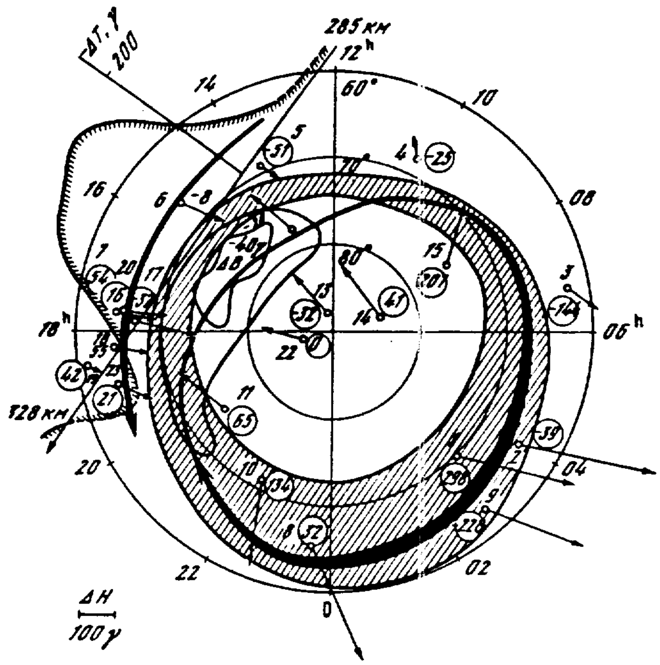

Figure 15. The region of negative ΔT on the basis of Kosmos-321 and ground station data during the substorm of March 4, 1970

The concept of the polar auroral oval has found a natural explanation in the asymmetry of the magnetosphere in the day-night direction and a number of physical processes at the force line interface controlled by the solar wind and taking part in the rotation of the earth.

However in literature published from 1970 through 1975 inferences were made that the zone of auroral and magnetic activity had a more complex topology. In a series of studies conducted by the Siberian IGIRWP the authors present arguments in favor of the existence of two horseshoe-shaped zones of particle penetration. It was assumed that there is a gap between the day and night portions of the zones and that aurorae in the day and night sectors are due to different physical processes.

Experiments conducted with the ISIS-2 satellite revealed a second belt of active particle penetration where diffuse polar aurorae often appear in the day sector. This belt is less eccentric with respect to the magnetic pole than the polar auroral oval, which constitutes the main characteristic of the polar regions [72].

THE EQUATORIAL IONOSPHERIC ELECTROJET

In 1922 magnetograms from the newly constructed Huancayo Magnetic Observatory (12 degrees S, 75.3 degrees W, geomagnetic latitude of 0.6 S) revealed that the diurnal variation

of the horizontal component of the geomagnetic field H had a surprisingly large amplitude on magnetically calm days. The other two components Z and D behaved normally.

15 years later the renowned geophysicist MacNeish conducted the first study of this effect in a spherical harmonic analysis of calm diurnal variations using data from a number of observatories on the American continent, including data from the Huancayo Station. The current system he calculated had force lines heavily bunched in the plane of the equator, which distinguished it from the current systems of calm solar diurnal variations calculated by Chapman.

In 1945 Fleming and Chapman initiated a study of S_q variations along the longitude of Huancayo by a chain of stations situated along the meridian. These studies revealed a strip near the equator where anomalously high S_q variations of field H were observed. Then they remembered that in 1942 Walter had detected a similarly high anomalous variation of the horizontal component in Uganda.

In 1947 Egedahl determined the relationship of the amplitude of the anomalous S_q variation to distance from the equator, and it became obvious that this phenomenon is controlled by the equator of inclination, where $J = 0$. Chapman named this region the "electrojet."

The electrojet is an eastern current which is manifested only on the dayside but covers the entire earth. A large number of publications have been devoted to studies of the morphology of this phenomenon on the basis of ground magnetic observatory data. Critical overviews of results obtained in recent years are given in [74-76].

Calm diurnal variations are induced by the tidal movements experienced by the highly conductive layers of the lower ionosphere. On the day side (now we know that there are no S_q currents on the night side) in the northern and southern hemispheres there are two current vortices. In the northern hemisphere the vortex runs counterclockwise, while in the southern hemisphere it runs clockwise. Both vortices have the same direction near the equator, from west to east, where the current is stronger. A formal spherical analysis of S_q variations of a global network of observatories has led to this picture. The physical conditions responsible for the existence of the electrojet can be summarized as follows: the conductivity of the ionosphere depends on the strength and direction of the magnetic field, the frequency of particle collisions, electron density, and wind direction and velocity. One conductivity peak is located in the E layer at an altitude of 110 to 120 kilometers.

On the magnetic equator the force lines run parallel to the earth's surface and to the north. Because the ionosphere is thin by comparison with its horizontal dimensions, current in it flows parallel to the surface of the earth. Vertical currents are impossible due to nonconductive upper and lower boundaries. This restriction leads to a significant increase in conductivity in a direction perpendicular to H. The electrojet consists of Pedersen current and an additional Hall current running toward the east.

The significant increase in conductivity perpendicular to H is also the reason for the increase in current in a narrow belt near the equator of inclination.

In reality the physics of processes in the equatorial ionosphere are just as complex as the morphology of the electrojet. The electrojet primarily induces current in the conductive layers of the earth and the field observed on the surface of the earth is the sum of these effects. The conductivity of the earth differs at different longitudes, which determines the characteristics of the field.

Eastern current is the primary but not the only consequence of the complex physical processes which occur in the equatorial ionosphere. There are meridional currents [77], and sometimes western current flows which distorts the typical appearance of the electrojet or sometimes even compensates for it [78, 79]. The small number of stations made it impossible to resolve decisively the question of whether the center of the electrojet is aligned with the equator of inclination.

Magnetospheric currents induce currents in highly conductive layers on the equator, making the picture even more complicated. Conductivity should depend on the actual magnetic field, which in turn determines differences in the intensity of the electrojet. The most interesting problem involves the possibility of using the electrojet to study the conductivity of the earth at different longitudes.

Direct studies of magnetic electrical fields and particle drift velocity in the electrojet were conducted from 1950 through 1968 using rocket mounted magnetometers and radar devices in the equatorial region. These experiments [80] provided proof of the existence of a current system in the E layer of the equatorial ionosphere on the day side and its absence on the night side. Satellites provided new opportunities for studying the electrojet.

The Kosmos-321 satellite crossed a region of the equator at altitudes of 250 to 260 kilometers on the day side and at altitudes of 370 to 420 kilometers on the night side. Thus, the distance of the satellite from the layer of the ionosphere where current flows was approximately equal to the altitude of the current layer above the surface of the earth. The satellite's quantum magnetometer, which measured the field scalar, in fact measured only the magnetic field of eastern current and did not even sense the magnetic field of meridional currents.

The effect of the electrojet could have been clarified by analyzing the differences ΔT between measured and calculated field values. Using a theoretical model with a Gaussian series with $n = m = 10$, differences ΔT could have wavelengths of 1800 to 3600 kilometers. The field gradients associated with the effects of the electrojet should differ noticeably from ΔT gradients. This constituted the basis of a procedure for isolating the effect of the electrojet. The effects of the electrojet in the magnetograms of the Kosmos-321 were clarified and studied in [81].

Figure 16 provides magnetograms associated with the effect of the equatorial jet in the noon hours. Magnetograms obtained on the night side on orbits 672 and 674 are given as examples. The magnetic effects of the electrojet at different longitudes differ in details, with respect to their peak values. This agrees with the variability of the electrojet known from ground data. The distance between points of the magnetograms where ΔT differs noticeably from zero (more than 5 gammas) varies from 7.5 to 9 degrees. Consequently the width of the electrojet 2b, where its effect is perceptible, is 750 to 900 kilometers. This is somewhat

greater than the width indicated in [76], but is close to the width of the region where the probability of the occurrence of a sporadic E layer is 3% [82]. The "effective" width of the electrojet, for which one may theoretically assume a width for the ΔT curve of 0.7 times its maximum value, is 320 to 380 kilometers. 2b = 350 kilometers is assumed to be the average.

The amplitudes of the effect of the electrojet recorded by the satellite's magnetometer vary from 76 gammas (orbit 499) to 20 gammas (orbit 468). Most often the peak value of ΔT is approximately 30 gammas. Peak values reveal no clear relationship to longitude. But such a relationship was revealed by means of statistical methods employed in processing ground observations, such as the difference in the intensity of the electrojet on the American continent (λ = 280 degrees) and in India (λ = 80 degrees). Apparently the effect of a number of factors makes the picture more complicated and masks the relationship between the intensity of the electrojet and geomagnetic field strength.

ΔT peaks were observed on orbits 621 and 622 at latitudes of 8 degrees 10, 8 degrees (λ = 59.5 degrees E), and 9 degrees 14.4' (λ = 82.8 degrees E). These data may be compared with the latest determinations of the location of the magnetic equator made in India: 8 degrees 49.6' (λ = 77 degrees E), 8 degrees 54.1' (λ = 77.5 degrees E), and 8 degrees 58.6' (λ = 78 degrees E). Apparently, if the effect of the electrojet is not distorted by the effect of magnetospheric fields and induction effects, the peak of curve ΔT is observed above the equator of inclination (J = 0).

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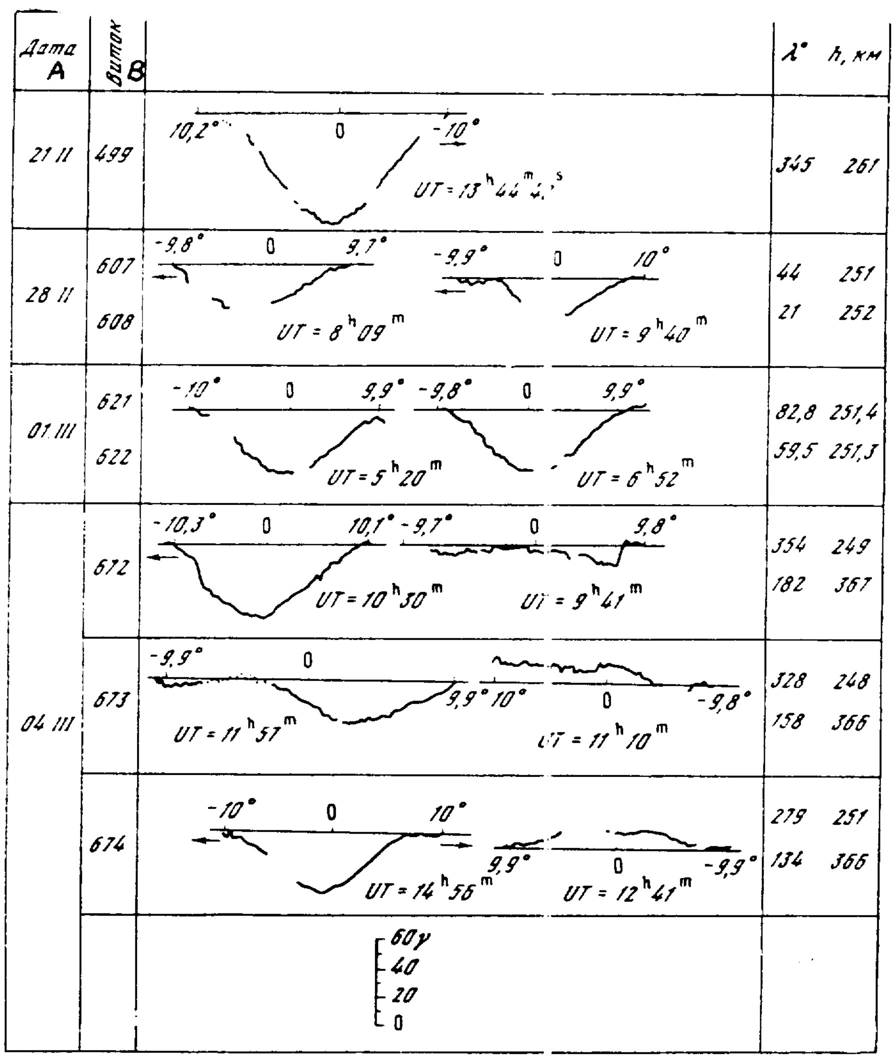

Figure 16. The effect of the equatorial electrojet as a function of magnetic inclination J (magnetic equator J = 0)

Key: A. date B. orbit

On several orbits the satellite crossed the equator near ground stations, which was used to compare ground and satellite magnetograms. The satellite magnetograms could have been compared with the magnetograms of ground observatories within the framework of a model examined by MacNeish [83] and subsequently by Chapman [73]. An outer, infinitely long current layer with a width of 2b located at an altitude of h above the surface of the earth, induces a current of equal intensity and opposite sign in the earth in a layer with a conductivity of $\sigma = \infty$ lying under a layer with a thickness of d and a conductivity of $= 0$ (Figure 17). The magnetic field of this current system measured by a satellite at an altitude of h above the surface of the earth and a distance x from the center of the current layer is given by a formula found in [81]:

$$\Delta H_c = \frac{C}{b}\left[\operatorname{arctg}\frac{2b(h_c - h)}{(h_c - h)^2 + x^2 - b^2} - \right.$$
$$\left. - \operatorname{arctg}\frac{2b(h_c + h + 2d)}{(h_c + h + 2d)^2 + x^2 - b^2}\right],$$

where C is the intensity of the current.

On the surface of the earth this formula looks like

$$\Delta H_3 = \frac{C}{b}\left[\operatorname{arctg}\frac{2bh}{h^2 + x^2 - b^2} + \right.$$
$$\left. + \operatorname{arctg}\frac{2b(h + 2d)}{(h + 2d)^2 + x^2 - b^2}\right].$$

From Figure 17 and the formulas it is apparent that current induced in the conductive layers of the earth amplifies the field of the outer current layer on the surface of the earth and gets weaker at the altitude of the satellite. Thus, from experiment data we know the ratio

$\Delta H_c/\Delta H_3 = f.$

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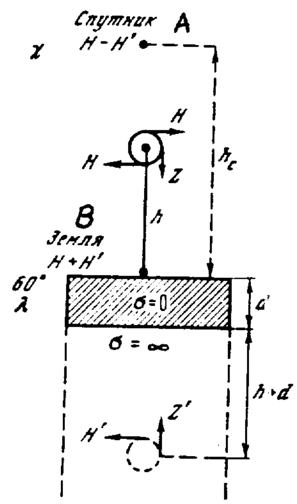

Figure 17. A model for determining the effect of the electrojet at satellite flight altitude

Key: A. satellite B. earth

There are different estimates of the "effective" width of the electrojet 2b. In the model chosen 2b is a uniquely unknown quantity and d is the depth of the nonconductive layer. By choosing values of 2b and d so that measured field profiles will optimally agree with calculated profiles (Figure 18), one can estimate the depth of the nonconductive layer. Data from the Kosmos-321 were used for these calculations in [81] and for more precise calculations in [84] by L. L. Vanyan, E. B. Faynberg, and N. Ye. Genis.

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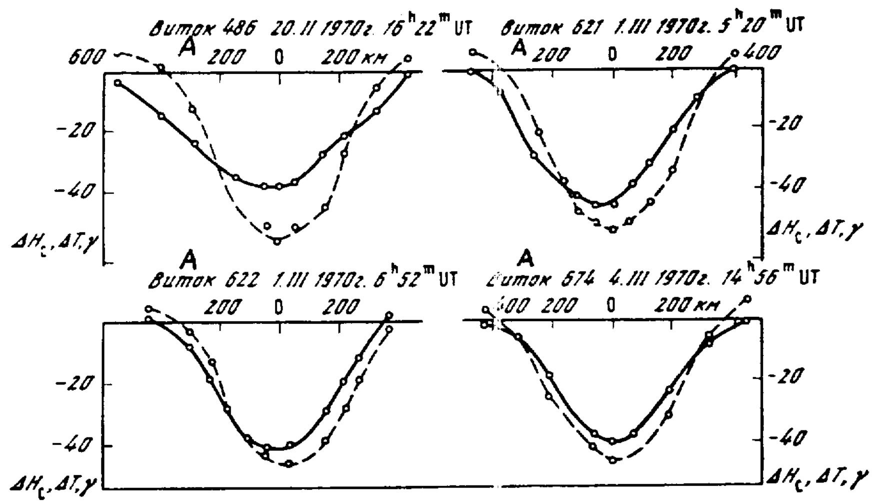

Figure 18. A comparison of observed and calculated values of ΔT of the equatorial electrojet

Key: A. orbit

Satellite overflights of observatories may be used for more precise determination of f. According to [84], f was equal to 0.54, 0.48, 0.49, and 0.6 instead of 0.33, which was assumed in [81].

The choice of an effective width for the electrojet is less clear-cut. For a current layer model, a width at an altitude of 60 to 70% of maximum field intensity, which is 400 to 500 kilometers, was chosen as the effective width. In these estimates the depth of the nonconductive layer varies from 305 to 515 kilometers. In fact the earth's mantle has a finite conductivity and taking this into account [84] led to a conductive layer depth of approximately 250 to 380 kilometers.

Despite the uncertainty of these estimates, one may still consider it proven that the MacNeish-Chapman induction model correctly describes the main features of the process in the sense that the electrojet is associated with a significant induction effect.

Although the rotation of the sectoral structure of the interplanetary field with the period of rotation of the sun leaves little doubt that it is solar in origin, this was first directly proven by Wilcox and Ness from 1964 to 1967, who compared interplanetary fields and the fields of the visible face of the sun (photospheric fields) [89].

A year later the average strength of the field of the visible face, the average strengths of sunspot fields, and the average strengths of interplanetary fields observed by the Explorer 33 and Explorer 35 satellites were compared [90] (Figure 19). A 4.6 day observation time shift of the magnetograms was accompanied by excellent sign agreement between the interplanetary field and the overall field of the photosphere. This time is approximately equal to the time it takes for solar wind plasma to travel from the sun to the earth at an average velocity of 400 kilometers per second. Subsequently it was demonstrated that recalculation of the strength of the photospheric field starting from some "surface of sources" leads to a reasonable agreement between interplanetary fields and the overall field of the photosphere not only with respect to their signs but also their magnitudes.

The average sunspot fields and interplanetary field do not manifest any noticeable correlation. This has a natural explanation. In order for a field to be "drawn out" from the sun, kinetic energy density, primarily the density of the energy of directional motion of solar wind particles, must exceed magnetic energy density. This condition can be written as follows:

$$^1/_2\, m_i n v^2/(H^2/8\,\pi) = g \gg 1,$$

where m_i, n, and v are the mass, concentration, and velocity of solar wind ions respectively.

In sunspots magnetic energy density is hundreds of times greater than the kinetic energy of plasma motion. On the other hand, outside active regions, where low intensity large scale fields are observed (in the sun's atmosphere and corona), magnetic energy density is 10 to 100 times lower than the kinetic energy of plasma motion. It has been found that the boundary between large scale photospheric fields of different polarities runs north to south on both sides of the equator in a large latitudinal belt. These boundaries also constitute the boundaries of interplanetary field sectors.

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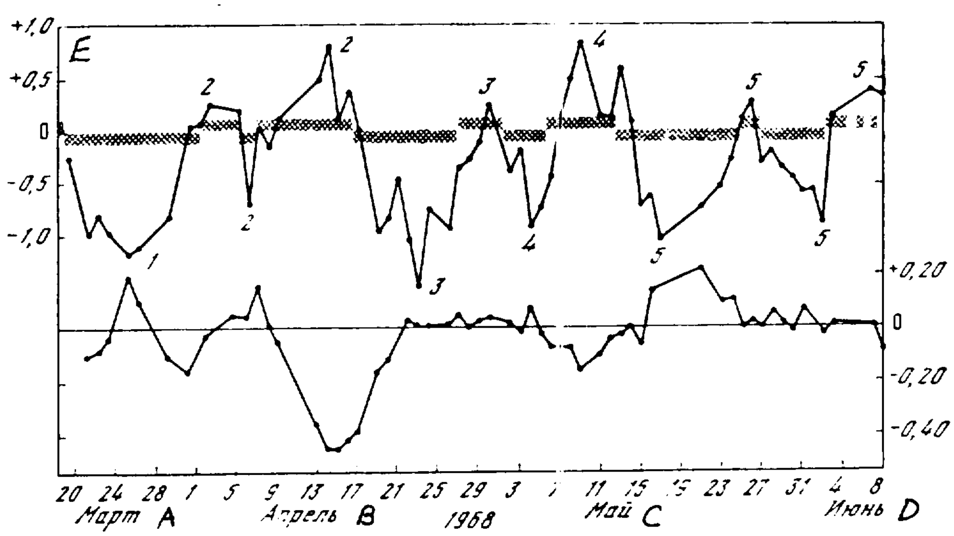

Figure 19. A comparison of the signs of the interplanetary field (dashed regions) with the sign of the average field of the visible face of the sun (top curve) and the average field of sunspots (bottom curve)

Key: A. March B. April C. May D. June E. gausses

Thus, observations of average photospheric fields using the "entire face" method [90] may be used to predict the sectoral structure of the interplanetary field. However a more effective method of determining the sign of interplanetary magnetic fields was discovered in observations of magnetic field variations at near polar stations on the earth's surface.

THE SECTORAL STRUCTURE AND VARIATIONS OF THE GEOMAGNETIC FIELD ON THE EARTH'S SURFACE

The fact that geomagnetic disturbances tend to recur with the period of solar rotation compelled researchers to look for regions on the visible face of the sun where magnetically active radiation is generated. The renowned German physicist Bartels called them M-regions [91]. The search for M-regions and their identification with specific formation on the sun has its own history. Bartels himself noted that M-regions are frequently not associated with sunspots. S. K. Vsesvyatskiy and his colleagues identified (1944-65) [92] M-regions with helmet shaped coronal rays (Figure 20). E. R. Mustel suggested that bright areas on photographs of the visible sun obtained in calcium lines, or calcium floccules, are magnetically active sources.

Comparisons of variations in the concentration, velocity, and temperature of solar wind particles and indices of magnetic activity on the earth revealed a correlation between these quantities. 10% or more variations of the first may be compared only with slight changes in magnetic and auroral activity.

It turned out that characteristics of the structure and direction of interplanetary magnetic fields, boundaries of sectors of different polarities of the magnetic field, and irregularities in interplanetary magnetic fields are highly efficient in generating disturbances on the earth [94]. Within each sector plasma parameters (velocity, concentration) reach peaks in the vicinity of the leading boundary of the sector. The geoefficiency of boundary regions could have been related to these irregularities in the solar wind.

Even greater irregularities could be assumed along the front of the shock wave which arises in the motion of a faster corpuscular stream and the slow-moving surrounding solar wind.

Direct comparisons of magnetic activity indices and the interplanetary field strength scalar revealed that they are in better correlation but that the analytical relationships between the first and second are cumbersome, which suggests a definite role for additional pecularities. This hypothesis was strengthened by the fact that magnetic energy density in the solar wind is 100 times less than radiation energy density. Consequently, the efficiency of the interplanetary field is not determined solely by its strength.

The relationship between the index of polar activity and solar wind parameters was established by comparing it with certain field components. For example, the AE index (which characterizes activity in the area of the auroral electrojet) manifests a clear correlation with the magnitude and time of action of the southern component of the interplanetary field B_z when solar wind dynamic pressure P_o is taken into account [95]. The extent of geomagnetic activity proved to be dependent on the angle between the axis of the dipole and the direction of the solar wind stream.

However an even clearer relationship to the sign and amplitude of the interplanetary field was established for a certain type of variations in the near polar regions of the earth observed during magnetically calm periods. They had already been under study for a long time (see Ya. I. Feldshteyn's overview of 1975 [97]) and the simple establishment of their relationship to the strength and sign of interplanetary magnetic fields made it possible to clarify the mechanism and nature of these variations. Moreover, now one can use recordings of magnetic field variations at near polar stations to form an opinion of the sign of individual components of the interplanetary magnetic field. This observation was first made independently by the Soviet geophysicist S. Mansurov [99] and the Danish geophysicist Svalgaard [98].

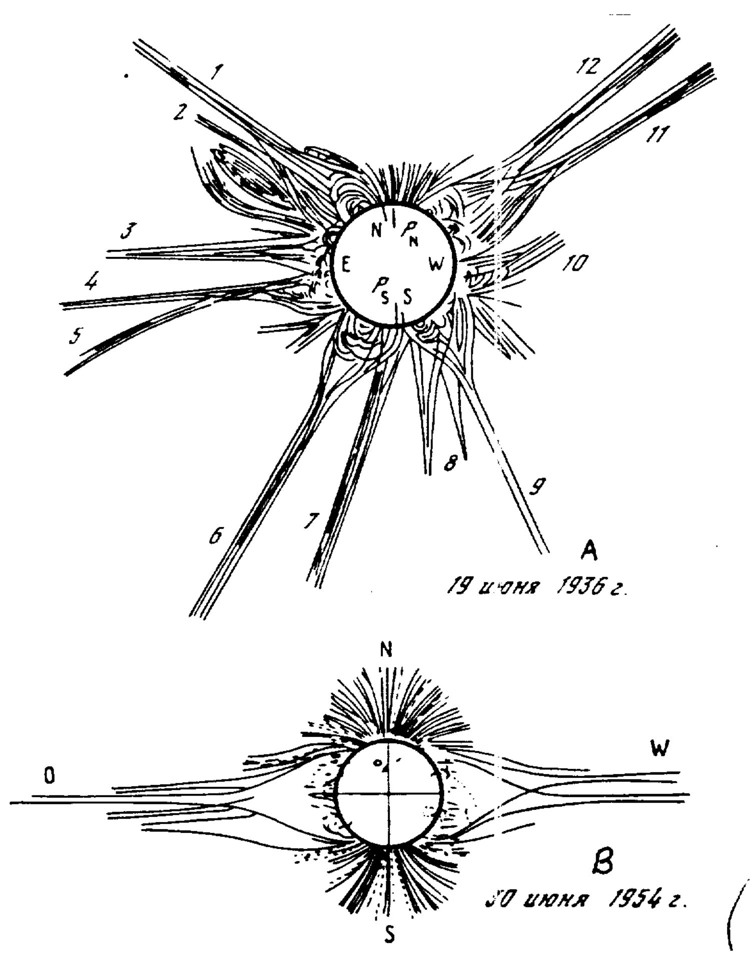

Figure 20. The helmet shaped structure of the solar corona during sunspot peaks and valleys

Key: A. June 19, 1936 B. June 30, 1954

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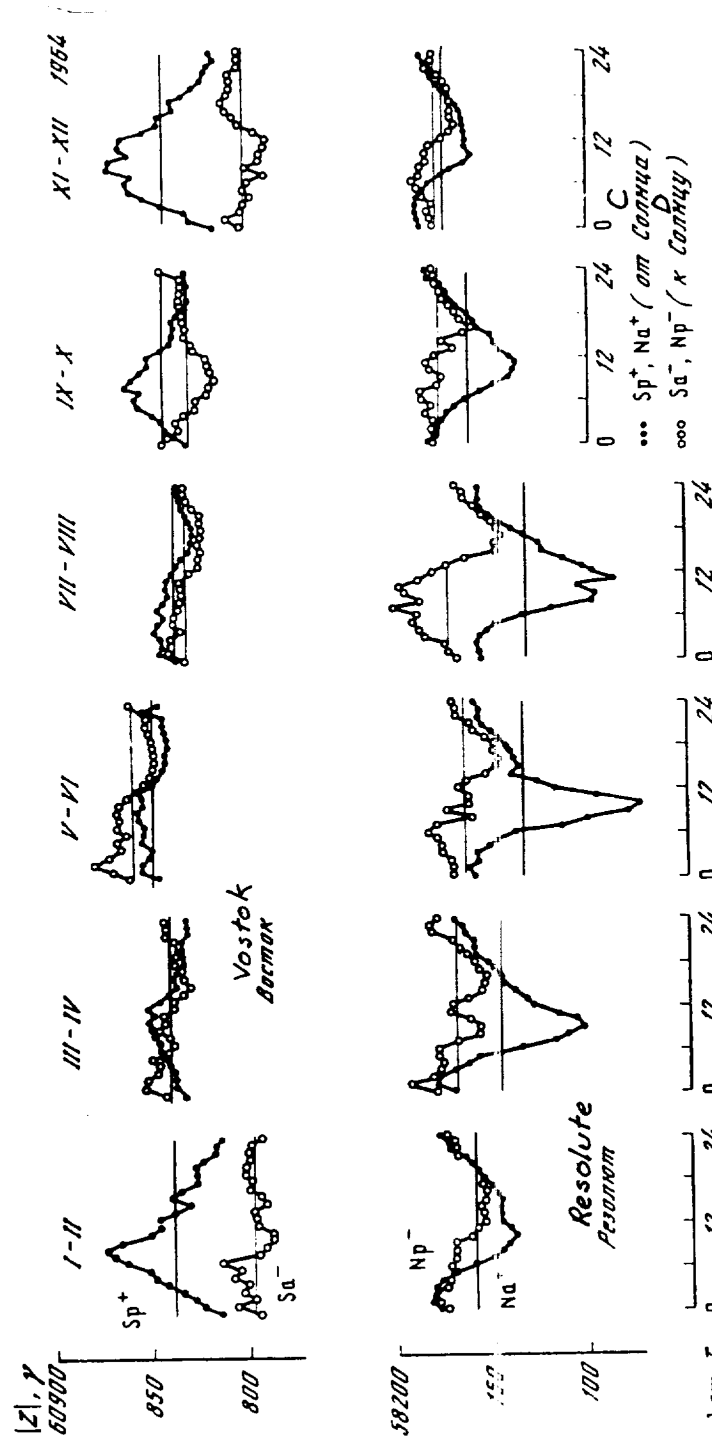

Figure 21. The signs of the variations of the modulus of the Z-component in the southern and northern hemispheres for different interplanetary field signs

Key: A. east B. resolute C. away from the sun D. towards the sun

The absolute value of the vertical component of the geomagnetic field at a near polar station in the northern hemisphere (Thule, Θ = 86 degrees) increases if the interplanetary magnetic field is directed toward the sun and decreases if it is directed away from the sun. The opposite relationship between changes in the modulus Z and changes in the sign of the interplanetary field has been observed at a southern hemisphere station (Vostok, Θ = -88 degrees). Thus, the additional field leading to a change in the absolute value of the vertical component is directed away from the earth in both hemispheres when the interplanetary field is directed away from the sun and towards the earth when the interplanetary field is directed towards the sun (Figure 21).

Intensive research on this effect based on ground and satellite data conducted in recent years (see overviews [100, 97] revealed that this relationship is sometimes violated and that variations in the near polar regions of the earth are in better correlation with the direction of the azimuth (east-west) component of the interplanetary field in the plane of the ecliptic. This was established independently and simultaneously by the Soviet geophysicists Ya. Feldshteyn and L. Sumaruk [101] and the Danish geophysicist Friis-Christensen [102].

The agreement is best when the moments of sign changes Y_{SE} are time shifted 25 to 60 minutes. As was disovered, the delay in ground changes ΔZ relative to changes in Y_{SE} is determined by the effect of induction in the conductive layers of the earth.

When the Y_{SE} component runs from the morning side to the evening side ($Y_{SE}>0$), values of Z are below the undisturbed level, while when
$Y_{SE}<0$, the values of Z are above the undisturbed level, and when Y_{SE}
= 0 the variations are equal to 0 (Figure 22). The direction of the azimuthal component is related to the direction of the radial component, because the interplanetary field on average runs in an Archimedean spiral. That is why the relationship between the sign of the radial component and the sign of the variation of the Z component in the near polar region was the first to be observed. However, when irregularities in the solar wind led to a change in the direction of the Y_{SE} component (while the sign of the radial component stayed the same), the correlation between the radial component and the Z component deteriorated.

Variations in Z reach 150 gammas in the summer and 15 gammas in the summer and at the equinoxes variations are high during the day and low at night. All this leaves no doubt that variations are due to the current system in the ionosphere whose conductivity is greatly controlled by solar illumination.

A mechanism of reconnection of the interplanetary field and polar force lines of the geomagnetic field resulting in the appearance of an electrical field in the polar cap which penetrates the polar ionosphere [103] has been proposed for the purpose of explaining the generation of a current system by the polar cap which depends on the magnitude and sign of the azimuthal component of the interplanetary field. Models have been specifically developed for this type of variations by Soviet [104] and foreign [105] scientists.

Observations in the polar cap during disturbances have revealed a special type of disturbance known as the DP-pole [106] limited to the region $\Phi > 75$ degrees with a peak intensity at $\Phi \sim$ 83 degrees on the day sign during the summer. As Yawasaki has suggested,

DP-pole type disturbances are due to rotation of the vertical component of the interplanetary field $+B_z$ to the north. In 1967, on the basis of observations of the interplanetary field made by the Venera-4, Sh. Dolginov indicated that variations in the northern component of the interplanetary magnetic field may affect magnetic activity in the polar regions. In the process he indicated that an increase in the northern component may lead to reconnection of force lines in both polar caps, in contrast to variations in the southern component B_z , whose increase is effective in the reconnection mechanism in the equator. DP_i (Bz) type variations also occur during calm periods.

Thus, one of the most important achievements of the second decade in space was the establishment of the decisive role of the sign and magnitude of the components of the interplanetary magnetic field in the development of magnetic activity on the surface of the earth. These relationships are most clearly manifest in the polar regions of the earth.

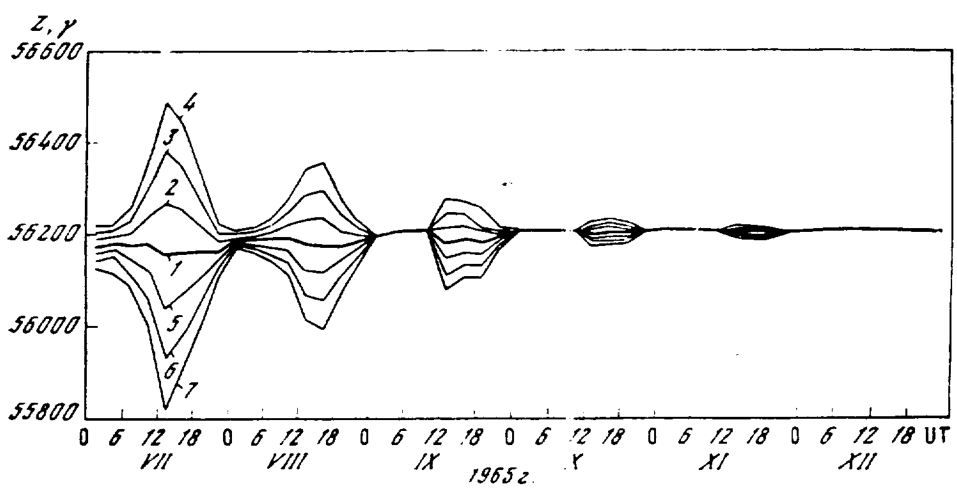

Figure 22. Diurnal variations of Z in 1965 for different values and signs of Y
1-7: 0, -3, -6, -9, +3, +6, and +9γ respectively

In turn these relationships have provided researchers with a new and accessible tool for studying, predicting, and diagnosing conditions in interplanetary space and diagnosing the magnetic state of the sun which involves observing magnetic field variations at several optimally selected magnetic variation stations in near polar regions on the surface of the earth. At present the Soviet Union and United States make regular determinations of sign of the sectoral structure of the interplanetary field using readings from the Vostok Station in Antarctica and the Thule station in Greenland.

GEOMAGNETIC FIELD FLUCTUATIONS

Among the diverse types of geomagnetic field variations controlled by external sources a special place is occupied by geomagnetic field fluctuations ranging from thousands of a hertz to several hertz.

According to current notions, geomagnetic fluctuations are hydromagnetic waves in the geomagnetosphere and outside it, and like any wave process in matter, depend on the physical properties and characteristic dimensions of the space where the fluctuations are generated and propagated. It is for this reason that geomagnetic fluctuations have proven to be a tool for diagnosing the magnetosphere and interplanetary space. One can use V. A. Troitskaia and A. V. Gugliemi's article [109] to familiarize oneself with the results of this fruitful research, which was conducted toward the beginning of the second decade in space. The current status of this topic is discussed in a monograph written by the same authors [110], who were involved in the development of this trend.

Objects of research included the places where geomagnetic fluctuations are generated, the variation of the spectrum of fluctuations and their energy in relation to variations of the characteristics and structure of the interplanetary field, the intensity of the solar wind, the dimensions of the magnetosphere, the phase of a disturbance, and the prospects for practical application of fluctuations. A significant contribution in this field was made by research conducted by the Polar Geophysical Institute, the IGIRWP, and the IKI. Table 3 illustrates the effectiveness of using methods of wave diagnosis for the magnetosphere and interplanetary space [110].

Also of interest are the relationships between the level of fluctuations and the phase of interaction of the geomagnetic field with successive structural features of interplanetary streams from powerful solar flares [111], and the relationships of the fading of the amplitudes of individual types of short period fluctuations in the vicinity of sectoral structure boundaries.

Because the spectrum of short period geomagnetic field fluctuations is similar to the spectra of electromagnetic oscillations of living organisms, combined study of these processes is extremely important in light of correlations which have been discovered in the activity of short period fluctuations and activity in the biosphere [112].

Table 3.

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Тип пульсаций A	*Параметр или процесс* B	C *Метод диагностики*
Жемчужины 1	1 Концентрация холодной плазмы Энергия резонансных протонов	Дисперсионный анализ. Анализ скачков несущей частоты 1
	Медленные нестационарные процессы (усиление и распад спокойного кольцевого тока, слабые электрические поля, перемещения плазмопаузы)	Анализ медленных вариаций несущей частоты 2
Непрерывные пульсации 2	2 Положение подсолнечной границы магнитосферы. Напряженность межпланетного магнитного поля.	Использование эмпирических связей периода колебаний с исследуемыми параметрами 3 2
	Крупномасштабные неоднородности межпланетного магнитного поля	Анализ вариаций огибающей амплитуды колебаний 4
Гигантские пульсации 3	Концентрация плазмы в вершинах силовых линий 3	Анализ зависимости периода колебаний от геомагнитной широты 3
	Крутизна спада концентрации плазмы вдоль силовых линий	Анализ неэквидистантности гармоник
Широкополосные 4 всплески пульсаций	Инжекция энергичных частиц из нейтрального слоя хвоста магнитосферы в зону сияний. 4 Периодичные процессы в геомагнитном хвосте	Анализ спектра и периодичности шумовых всплесков в окрестности полуночного меридиана 4
Гидромагнитные завывания 5	Нестационарный дрейф энергичных протонов. Электрические поля во время магнитосферных суббурь 5	Анализ нестационарности спектра. Измерение величины западного «дрейфа частоты» 5
Авроральная ажитация 6	Нестационарный дрейф электронов, инжектируемых во время магнитосферных суббурь 6	Анализ перемещения характерных деталей спектра колебаний от полуночи на восток 6
Цуги колебаний 7	Положение южной границы зоны сияний в полуночном секторе 7	Использование эмпирической связи периода колебаний с широтой южной границы зоны сияний 7

Key: A. type of fluctuation 1. beads 2. continuous fluctuations 3. gigantic fluctuations 4. broad band fluctuation surges 5. hydromagnetic twistings 6. auroral agitation 7. oscillation trains B. parameter or process 1. cold plasma concentration, resonant proton energy, slow dynamic processes (amplification and decay of calm ring current, weak electrical fields, plasmopause shifts) 2. position of the subsolar boundary of the magnetosphere. interplanetary magnetic field strength. large scale interplanetary magnetic field irregularities 3. concentration of plasma at force line vertices. rate of decrease of plasma concentration along the force lines 4. injection of energetic particles from the neutral layer of the tail of the magnetosphere into the auroral zone. periodic processes in the geomagnetic tail. 5. dynamic drift of energetic protons. electrical fields during magnetospheric substorms 6. dynamic drift of electrons injected during magnetospheric substorms 7. the position of the southern boundary of the auroral zone in the midnight spectrum C. diagnostic procedure 1. dispersion analysis. analysis of abrupt changes in the carrier frequency. analysis of slow carrier frequency variations 2. the use of empirical relationships between the period of fluctuation and the parameters in question. analysis of variations of the fluctuation amplitude envelope 3. analysis of the relationship of the fluctuation period to geomagnetic latitude. analysis of variations in the distance between harmonics 4. analysis of the spectrum and periodicity of noise surges in the vicinity of the midnight meridian 5. analysis of spectrum dynamism. measurement of the amount of western "frequency drift." 6. analysis of the shift of characteristic details of the fluctuation spectrum from midnight to the east 7. the use of an empirical relationship between the fluctuation period and the latitude of the southern boundary of the auroral zone.

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16. Abstract

Soviet scientists and scientists from a number of other countries marked the second decade in space with intensive experimental and theoretical research on the solar wind, the structure of the "calm" geomagnetosphere, the space-time structure of the development of substorms, and the extent of magnetism among the planets of the solar system. The results achieved in this period include proof of the solar origin of interplanetary fields and determination of the relationship of the sign and magnitude of interplanetary fields to the sign and magnitude of the total magnetic field of the visible face of the sun.

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